SOLAR CHIMNEY DESIGN
INVESTIGATING NATURAL VENTILATION AND COOLING IN OFFICES WITH THE AID OF COMPUTER SIMULATION

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Abstract

Solar chimney design is investigated as a means of improving natural ventilation and passive cooling in office buildings. Existing scientific research and built precedents are generally limited; literature review findings on various features of solar chimneys were categorised and used to develop a building simulation strategy. Using UK climatic data, simulations were performed on several computer models in order to investigate solar chimney performance during a single day period and an entire cooling season.

Passive cooling with a solar chimney is possible but actual reduction in temperatures in most cases examined could be negligible. Cooling potential is increased on still, warm days, while the prospects for night cooling are further improved. A solar chimney may help reduce considerably the occurrence of resultant temperatures at or above the 25 C° and 28 C° thresholds. Solar chimney width, height, apertures and integral use of thermal mass are the most significant parameters for cooling.

Simulation results showed that a solar chimney can increase significantly natural ventilation rates. Total ventilation rates may be increased by at least 22%. During still days a solar chimney can enhance ventilation rates by 36% or more. Stack ventilation through a solar chimney is typically ~20% of cross ventilation; during night time this may increase to at least 40-45% and on still days it may reach 100% of typical cross ventilation rates.

Solar chimney induced stack ventilation and cross ventilation are interrelated. Resultant air flow patterns may have an important effect on convective heat transfers and thermal comfort. Climate and microclimate conditions should be an integral part of solar chimney design. Key aspects and recommendations regarding solar chimneys, passive cooling and natural ventilation are provided for design guidance and feedback in further research.

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Preface

“Reality is infinitely complex. Our knowledge of the world is always finite and therefore always incomplete. The marvel is that we function quite well in the world in spite of never fully understanding it. Our tool to deal with incomplete knowledge is modeling. A model is a small finite description of an infinitely complex reality: for the purpose of answering particular questions. The complexity of a model depends on the kind of questions we are seeking to answer.” Benjamin Kuipers, 1994, Qualitative Simulation, The MIT Press

"It is not at all simple to understand the simple."
Eric Hoffer

1. Introduction

1.1 Global warming and buildings

In recent years energy use and global warming have become daily subjects in news media around the world. A recent report from the World Wildlife Fund analyzing summer temperature data from 16 EU cities shows that some of the continent's capitals have been warming by as much as 2 °C in the last 30 years. The average maximum summer temperature in London has increased from 20.5 °C in the early 1970s to 22.5 °C in the last five years. This was followed by Athens and Lisbon (1.9 °C), Warsaw (1.3°C) and Berlin (1.2 °C). (Ashton J., 2005),

Countries in the European Union have agreed to reduce greenhouse-gas emissions between 2008 and 2012 by 8%, as outlined in the Kyoto Protocol. (EU, 2005) The UK has committed to an overall 12.5% reduction of emissions. Most of the burden for reducing greenhouse-gas emission will fall on the EU's energy, manufacturing, transport and farming industries but new guidelines and regulations are being introduced in the building industry.

1.2 Energy use and buildings

Buildings in the UK and other European countries consume approximately 40 to 50% of primary energy and are associated with about 50% of CO^2 emissions. (Santamouris et al. 1994) According to a survey (Energy Paper 66), energy for cooling in commercial office buildings amounts to 278,000 tones-of-oil-equivalent delivered energy. This represents slightly over 10% of the total energy consumed by commercial office buildings. In addition, according to the same survey, the percentage of full air-conditioned office space is also increasing; 7.5% of floor area was air-conditioned in 1970, 12% in 1980, 19% in 1990, and 27% in 1994. (Kolokotroni et al., 1999) More recently demand for room and packaged air conditioner has grown 23% between 2000 and 2003 while future demands are projected to increase by an additional 21%. (JRAIA, 2005)

Economic affluence and technological advances have exasperated the problem of unsustainable energy use though dramatic improvement in living standards. Thermal comfort during summer has become gradually more important yet, with the increasing energy prices, reduction of cooling loads by natural means has become a major priority for many consumers as well as electric utility companies. Peak electricity demands and resulting high costs of conventional cooling systems make the strategic management of air conditioning growth an important issue of industrialized countries. (Todorovich, 1991)

Offices are probably some of the most demanding buildings in terms of energy use. Increased occupancy levels and electrical equipment result in greater heat gains. Building use during peak external temperatures (summer season) and improved internal conditions further increase the need for cooling and fresh air. Modeling of standard air-conditioned office buildings has shown that energy demand for cooling always exceeds the need for heat, wherever the building is located. (Kolokotroni et al., 2005)

1.3 Bioclimatic design

Inexpensive and abundant energy have allowed designers to rely solely on technology to resolve the aspect of environmental control. Yet, integration of established methods of construction and innovative technologies has always been the key factor of successful buildings. The approach to building design is essential in producing buildings that are energy efficient.

Bioclimatic architecture is based on a combination of new and traditional methods of creating human habitats through an improved scientific understanding of natural principles such as climate and mechanisms of human response to environmental conditions. According to Olgyay's (1973) studies of regional architecture around the world, common characteristics can be found in buildings with similar climate conditions, while some of the differences are based on site context such as natural resources and culture. Olgyay used available scientific means to investigate further the relationship of climatic factors and human comfort. He devised a number of methods and tools which can be used to assess and employ the existing climate conditions into the design of buildings. Scientists such as Fanger, Givoni and Watson further explored the parameters of environmental control and helped establish current design principles.

Air flow patterns and ventilation rates are some of the most important aspects for controlling the environmental conditions within buildings as well as improving human comfort. Natural ventilation is increasingly explored as a feasible method for passive cooling and improved energy efficiency. Scientific developments and new computer software enable the integration of established principles of bioclimatic design with new concepts and strategies.

"As with passive solar heating and passive solar design, the study and application of passive cooling are a part of a multi-layered and multi-disciplinary process. It is especially important to treat the subject in conjunction with other aspects of architectural and engineering design and in the context of an overall environmental design strategy." (Santamouris et al., 1997)

The aim of this dissertation is to investigate through existing literature and the use of computer simulation the potential use of solar chimneys in enhancing the natural ventilation and passive cooling in an office building module, in the UK.

2. The role of ventilation in buildings

2.1 General Requirements

Ventilation in buildings can be naturally or mechanically induced or even a combination of both (hybrid ventilation) and fulfills a number of important functions related to health, thermal comfort and cooling. Table 2.1 provides a summary of general recommendations on building ventilation rates.

Table 2.1: Requirements and functions of ventilation

Requirement	ACH	l/m²	Function
Health	0.5-1	1-5	Provides O_2, displaces indoor pollutants
Air Quality	Depends on space / use		Ventilation dilutes and removes pollutants generated in a space (CO, CO_2, OC's)
Comfort	0.4-0.8	0.8.-4	Good ventilation strategies will provide thermal comfort and eliminate cold draughts.
Cooling	5-30	4-25	Ventilation can be used to cool a space, thus minimizing the need for air-conditioning and reducing energy use and CO2 emissions
Energy	Air change accounts for up to 50% of energy dissipation from buildings. Energy efficient design maximizes air quality while avoiding excessive energy loss.		
Sources: CIBSE Guide A, CIBSE AM 10			

2.2 Ventilation and Health

Ventilation is essential in providing oxygen (O_2) for respiration. Fresh air requirements for humans will depend on the level of activity taking place indoors. Table 2.2 provides recommendations for fresh air flow rates in relation to human activity indoors.

Ventilation is also very important in displacing hazardous indoor pollutants such products of normal human activity (CO_2), or gasses and particles originating in construction materials, furnishings or building equipment. (CO, VOC's) Adequate fresh air can prevent and even eliminate the development of microorganisms such as dust mites. (Davies et al., 2004) Table 2.3 provides some of the building relating diseases such as sick building syndrome that could be prevented or at least minimized by adequate ventilation.

Table 2.2: Fresh Air Requirements for respiration

Activity (adult male)	Metabolic Rate (W)	Flow rate to maintain room CO2 concentration at a given value assuming 0.04% CO_2 in fresh air (l/s)	
		0.5% CO_2	0.25% CO_2
Seated quietly	100	0.8	1.8
Light work	160-320	1.3-2.6	2.8-5.6
Moderate work	320-480	2.6-3.9	5.6-8.4
Heavy work	480-650	3.9-5.3	8.4-11.4
Very heavy work	650-800	5.3-6.4	11.4-14.0

Note: These values are based on CO_2 production rate of $7.2x\ 10^{-5}$ l/s

Source: Awbi H.B., Ventilation of Buildings; Spon Press, London 2nd Edition, 2003, Table 2.2, page 52

Table 2.3: Building related diseases

Disease	Symptoms	Causes
Rhinitis, Sinusitis	Stuffy, runny nose, postnasal drip, pale or erythematous mucosa	Direct occupational exposures, molds, laser toners, carbonless copy paper, cleaning agents pet
Asthma	Coughing, wheezing, episodic dyspnea, difficulty breathing	Dust, allergies, dust mites
Hypersensitivity pneumonitis	Cough, dyspnea, myalgia weakness	Molds, moisture
Organic dust toxic syndrome	Cough, dyspnea, chest tightness, feverishness	Gram-negative bacteria
Contact dermatitis (allergic)	Dry skin, itching, scaling	Molds, carbonless copy paper, laser toners
Contact urticaria	Hives	Office products
Eye irritation	Eye itching, irritation, dryness	Low relative humidity, volatile organic compounds particulates
Nasal irritation	Stuffy, congested nose, rhinitis	Low relative humidity, volatile organic compounds, particulates

Central nervous system symptoms or SBS	Headache, fatigue, irritability, difficulty concentrating	Volatile organic compounds, noise, lighting, work stress, carbon monoxide, cytokines from aerosol exposure
Legionnaires' disease	Pneumonic illness	Aerosols from contaminated water, humidifiers
Source: Diseases Related to Buildings, 2001 ASHRAE Fundamentals Handbook, p. 170		

Extensive urbanization and subsequently increased pollution and noise levels in cities pose a major design challenge in selecting an appropriate ventilation strategy for a building. This problem becomes more evident when considering natural ventilation techniques which require free movement of air uninhibited by filters and noise buffers. The orientation, size, location and degree of opening of any apertures as well the methods of ventilation become very important in minimizing pollution and noise.

2.3 Ventilation and thermal comfort

Human beings are homeothermic species; their body temperature is maintained within a very narrow range through a variety of thermoregulatory structural and physiological devices. In any environmental condition that the human body is exposed it must maintain a temperature of approximately 37° C (±0.5). Maintaining heat balance is the primary condition for achieving a neutral thermal sensation yet, even though the human thermoregulatory system can effectively create heat balance within relatively wide range of environmental conditions, comfort may not necessarily be achieved. (Fanger, 1970)

There are four main environmental factors that affect thermal comfort:

- Air temperature (dry bulb temperature)
- Mean radiant temperature
- Air speed
- Relative Humidity

The combination of dry bulb temperature and mean radiant temperature provide the Dry Resultant Temperature. This index adopted by CIBSE is primarily used for thermal comfort assessment and guidance and in practice it is equivalent to the operative temperature used in the ISO22 and ANSI/ASHRAE standards. (CIBSE A, p. 1-6)

Ventilation will have a direct influence on air temperature, air speed and humidity in a building while it may also affect indirectly mean radiant temperature. Air movement may increase psychologically the perception of cooling. Overall natural ventilation is often seen as a user friendly option and occupants tend to accept wider variations of indoor environmental conditions then they would with any mechanical methods.

2.4 Ventilation and cooling

Ventilation can provide significant cooling to buildings and occupants. This cooling takes place via convective heat transfer in the followings ways:

- Introduces cool, fresh air while displacing internal warm air
- Creates a comfort breeze which removes heat directly from occupants and equipment
- Directly removes heat stored in buildings thermal mass

Heat transfer by convection depends upon the temperature difference between the surface and the air, the surface roughness, the air velocity and the direction of heat flow. Convective heat transfer where there is significant air movement is a more complex phenomenon. (CIBSE Guide A, p.3-8)

Excessive ventilation rates (greater than 10 ACH) can be achieved by cross ventilation but cooling effectiveness is reduced and can cause discomfort. (CIBSE Guide A, p. 5-34)

Night time ventilation takes advantage of diurnal temperature swings to improve cooling. Furthermore it may be used to cool the building fabric, effectively transforming the building mass into a "cool" storage and thus allowing it to absorb more internal heat gains during the day. Table2.3 provides the approximate cooling capacity of the most common types of building ventilation.

Table 2.3 Range of cooling loads applicable to various technologies

Type of System	Typical range of cooling (W/m²) (approximate values)
Natural ventilation	10-35
Mechanical ventilation	20-40
Displacement ventilation	30 -50
Chilled ceiling + displacement ventilation	60 -100
VAV air conditioning	80- 150
Fan coil air conditioning	80 -150

Source: Technical Note AIVC 46, 1996, The role of ventilation in cooling non-domestic buildings, International Energy Agency

3. Natural ventilation

3.1 Types of natural ventilation

Natural ventilation is the process of supplying and removing air through an indoor space by natural means. There are two types of natural ventilation occurring in buildings: wind driven ventilation and stack ventilation. The pressures generated by the stack effect mechanisms are quite low (typical values: 0.3 Pa to 3 Pa) while wind pressures are usually far greater (~1 Pa to 35 Pa). The majority of buildings will rely mostly on wind driven ventilation yet stack ventilation can offer several benefits. The most efficient design for a natural ventilation building should implement both types of ventilation.

3.1.1 Wind driven ventilation

The static pressure of air is the pressure in a free-flowing air stream and is depicted by isobars in weather maps. Differences in static pressure arise from global and microclimate thermal phenomena and create the air flow we call wind. Dynamic pressure is the pressure exerted when the wind comes into contact with an object such as a hill or a building and it is related to the air density and the square of the wind speed. The impact of wind on a building affects the ventilation and infiltration rates through it and the associated heat losses or heat gains. Wind speed increases with height and is lower towards the ground due to frictional drag.

The impact of wind on the building form creates areas of positive pressure on the windward side of a building and negative pressure on the leeward and sides of the building. Thus building shape is crucial in creating the wind pressures that will drive air flow through its apertures. In practical terms wind pressure will vary considerably creating complex air flows and turbulence by its interaction with elements of the natural environment (trees, hills) and urban context (buildings, structures).

Typical building design relies on rules of thumb for harnessing the power of wind for the purpose of natural ventilation. Design guidelines are offered in building regulations and other related literature and include a variety of recommendations on several subjects such as:

- Building location and orientation
- Building form and dimensions
- Window typologies and operation
- Other aperture types (doors, chimneys)
- Construction methods and detailing (infiltration)
- External elements (walls, screens)
- Urban planning conditions

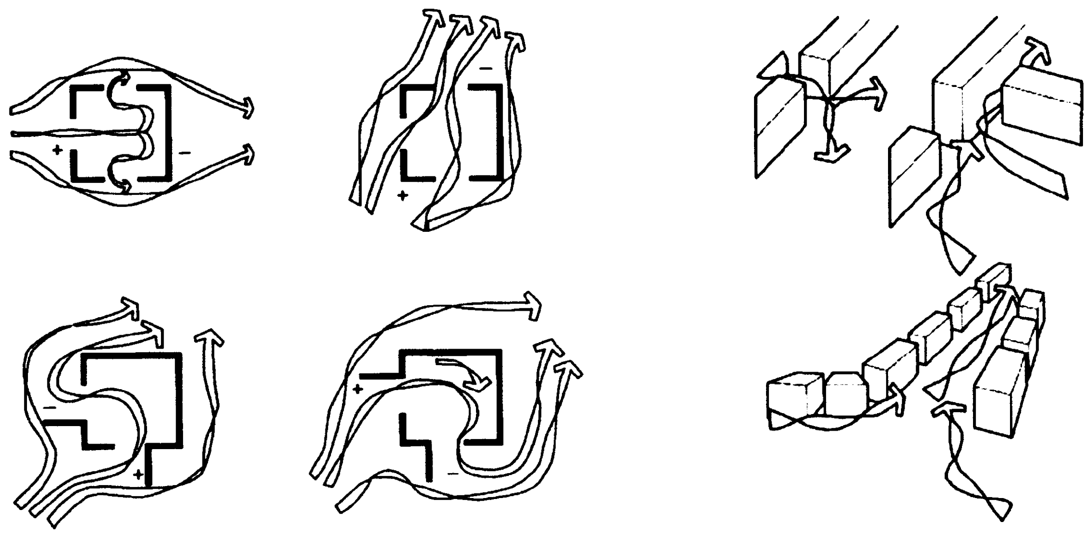


Image 1 Sketch guidelines on wind design and natural ventilation strategies
Source: P. Jones, Thermal Environment

Wind driven ventilation has several significant benefits:

- Great magnitude and effectiveness
- Readily available (natural occurring force)
- Relatively economic implementation
- User friendly (when provisions for control are provided to occupants)

Some of the important limitations of wind driven ventilation:

- Unpredictable and unreliable due to constant change and turbulence
- Design restrictions and difficulties in harnessing due to variations in speed and direction
- The quality of air it introduces in buildings may be polluted for example due to proximity to an urban or industrial area
- May create strong, draughts, discomfort.

3.1.2 Stack driven ventilation

Stack effect is temperature induced. When there is a temperature difference between two adjoining volumes of air the warmer air will have lower density and be more buoyant thus will rise above the cold air creating an upward air steam. Forced stack effect in a building takes place in a traditional fire place. Passive stack ventilators are common in most bathrooms and other type of spaces without direct access to the outdoors.

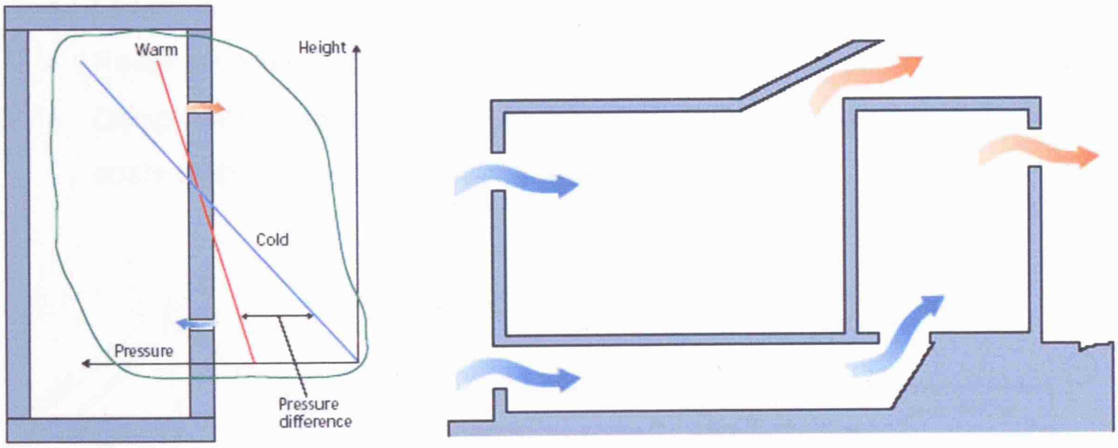


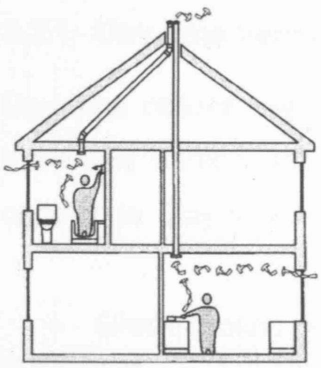
Figure 3.1.2.1 Representation of airflows in stack effect and an example stack driven ventilation
Source: Source: CIBSE AM10, p.16

In order for a building to be ventilated adequately via stack effect the inside and outside temperatures must be different so that warmer indoor air rises and escapes the building at higher apertures, while colder, denser air from the exterior enters the building through lower level openings. Stack effect increases with greater temperature difference and increased height between the higher and lower apertures. The neutral plane in a building occurs at the location between the high and low openings at which the internal pressure will be the same as the external pressure (in the absence of wind). Above the neutral plane, the air pressure will be positive and air will rise. Below the neutral plane the air pressure will be negative and external air will be drawn into the space. Stack driven ventilation has a number of considerable benefits:

- Does not rely on wind: can take place on still, hot summer days when it is most needed.
- Natural occurring force (hot air rises)
- Relatively stable air flow (compared to wind); reduced amplitude
- Greater control in choosing areas of air intake
- Sustainable method

Limitations of stack driven ventilation:

- Lower magnitude compared to wind ventilation
- Relies on temperature differences (inside/outside)
- Design restrictions (height, location of apertures) and may incur extra costs (ventilator stacks, taller spaces)



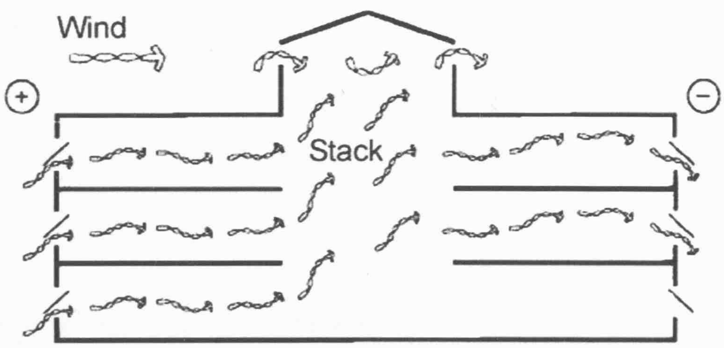


Figure 2 Typical stack ventilation in a small residential building and combination of wind and stack driven ventilation Source: P. Jones, Thermal Environment

Natural ventilation in buildings relies mostly in wind pressure differences but stack effect can augment this type of ventilation and partly restore air flow rates during hot, still days. With stack ventilation air inflow in a building does not solely rely on wind direction. In this respect it can provide improved air quality in some types of polluted environments such cities. For example air can be drawn through the backside or courtyards of buildings avoiding the direct pollution and noise of the street facade. Wind can augment the stack effect but also reduce its effect depending on its speed, direction and the design of air inlets and outlets. Therefore prevailing winds must be taken into account when designing for stack effect ventilation.

3.2 Methods of natural ventilation

Methods of building ventilation and cooling should depend upon the fabric, likely heat gains, type of use and occupancy. High gain buildings are more likely to need mechanical ventilation (and probably mechanical cooling) than low gain buildings. In many cases though, there might be ways of reducing or even eliminating this. In buildings with high 24-hour gains thermal mass is not so useful.

There are three basic methods of ventilating a building naturally:

- Day time ventilation
- Night time ventilation
- Air Infiltration

3.2.1 Day time ventilation

Day time natural ventilation is the most widely used ventilation method due to increased human activity and building use as well as external environmental conditions. Day time ventilation has several significant benefits:

- Great cooling potential when external temperatures are not very high
- Wind forces and stack effect are typically greater during the day
- Easier to implement and better user control
- Reduced security risk

There are however several limitations regarding day time ventilation:

- Greater amplitudes may cause drafts and discomfort
- Not as effective in cooling since temperatures are higher during the day
- Need to be restricted during extremely hot spells
- Usually pollution levels are greater during the day

3.2.2 Night time ventilation

Night ventilation is a very effective way to cool buildings and introduce fresh air during the night. New window technologies offering flexible and secure operation combined with a growing concern for energy saving have brought night ventilation to the forefront of environmental design strategies.

Night ventilation can be more effective than the equivalent daytime ventilation in regards to cooling. It was found that it can reduce cooling needs by about 40%. This is due to the fact that the outside temperatures are considerably lower during the night, heat gains are minimal and the ventilation period can be longer. (Gratia et al., 2004b) According to Breesch et al. (2005), natural night ventilation can improve thermal summer comfort more than an earth-to-air heat exchanger.

Night time ventilation has several significant benefits:

- Great cooling potential due to the lower ambient temperatures
- Allows pre-cooling of building
- Night time implementation does not interfere with building use and occupants
- Night time lower air pollution levels

Limitations regarding night time ventilation:

- Some security issues; may need automated controls.
- Lower rates of ventilation (reduced wind speeds)
- May need to rely more on stack driven ventilation

- Best implemented in buildings without night time use so that greater cooling of building fabric may be allowed

"Night ventilation is most effective in moderate climates such as the UK where the diurnal swing is sufficient that ambient temperatures at night fall below normal daytime internal comfort temperatures. It is suitable for buildings with periodic daily loads such as offices." (Barnard, 2002)

3.2.3 Air infiltration

Air infiltration is the term used to describe the unplanned leakage of air through a building due to imperfections in the structure, such as:

- Cracks around doors, windows, infill panels
- Service entries, pipes, ducts, flues, ventilators and
- Through porous constructions, bricks, blocks, mortar joints.

In many cases and for most of the year, infiltration alone may provide sufficient outdoor air to ventilate the building. However if air infiltration is uncontrollable, it can increase considerably convective heat losses (or even gains) resulting in higher utility bills and will often result in poor comfort levels due to drafts. Today most new buildings are built with increased air tightness but also have provisions for controlled air infiltration devices such as trickle ventilators.

3.3 Aspects of naturally ventilated offices

3.3.1 Internal Environmental conditions

One of the aims of natural daytime ventilation in summer is to lower indoor temperatures to the external ambient level. This is generally applicable if the external ambient temperature is in the range of 20–25 °C. Daytime ventilation can be utilized to conditions of ambient temperatures above 25 °C, provided the air humidity is low. The use of night cooling can reduce the indoor air temperature to levels well below the day time peak temperature and if used in conjunction with thermal mass it can reduce considerably the effects of solar and internal heat gains. Table 3.1 presents some of the features of natural ventilation in non-domestic buildings.

Table 3.1: Features of natural ventilation in non-domestic buildings

The building acts as the primary climate modifier.	Benefits	Greater design effort is required to ensure satisfactory operation
	Drawbacks	Simpler and more manageable environmental systems
Reduced reliance on mechanical plant	Benefits	Lower construction and maintenance costs
	Drawbacks	Upper limits of 30W/m²-40 W/ m² on total coincidental heat gains. Greater care is needed to avoid loss of flexibility in layout
Personal control of environment using operable windows	Benefits	Increased user satisfaction and productivity
	Drawbacks	Available only for occupants in perimeter. Not effective for deep plan buildings
Reduced energy used for ventilation and cooling	Benefits	Reduced operating costs and environmental friendly approach
	Drawbacks	Greater variation in internal conditions.

Source: Good Practice Guide 237, Natural ventilation in non-domestic buildings- a guide for designers, developers and owners, Best Practice Program; page 6

Recommended dresign targets for internal conditions of naturally ventilated offices are:

- The building should be designed not to exceed a dry resultant temperature of 28°C for more than 1% of the year and not to exceed 25°C for more than 5% of the year.

- Air movement in a naturally ventilated building may be used to offset higher dry bulb temperatures, but the air velocity should not exceed 0.8 m/s for cooling.
- If there is use of air-conditioning and the moving air is lower in temperature than the bulk air condition, then an air movement limit of 0.2 m/s should be used.
- Vertical temperature gradients should be limited to no more than 3°C through the occupied zone, and a maximum radiation asymmetry of 10°C for a cold vertical surface, 5°C for a warm ceiling. (Report 30, 1995)

3.3.2 Thermal Mass and natural ventilation

Thermal mass generally describes the ability of a buildings fabric to store heat and thus in regards to cooling, absorb and alleviate internal heat gains. Thermal mass can also be used to store "coolth". High density materials and constructions with good thermal absorptance such as masonry and concrete provide effective thermal mass when they are adequately exposed to the internal environment of a building. Usually the main structural core of a building can provide high thermal mass. The use of false floors and ceilings, carpets, tapestries and furniture can reduce considerably the thermal inertia of a building. Increasing the exposed area of thermal mass by using an undulating ceiling design or concrete ribs increases its effectiveness. (Gratia et al. 2003d)

The cooling performance of thermal mass, according to Barnard (2002), relies on three primary factors:

- The amount of cooling introduced into the building via night ventilation
- The heat transfer between air and the thermal mass
- The capacity of thermal mass to store cooling energy

Most buildings have sufficient mass in the form of the concrete used in the floor construction to effectively store the amount of cooling introduced at normal ventilation rates. (Barnard, 2002) The ability of thermal mass to absorb and store solar energy may also be used to induce air flows. It can help sustain

higher air temperatures in specific parts of a building (tops of atriums and ventilations shafts) thus enhancing stack effect and building ventilation rates.
Benefits of thermal mass:

- Absorbs and stores internal heat gains
- May increase the cooling capacity of ventilation, store "coolth"
- Allows greater freedom for occupants to open windows
- May be used to enhance stack effect

Limitations of thermal mass:

- May have increased building costs
- Could limit usable building space
- Shading/ limiting summer solar gains crucial
- Best effective with use of night ventilation
- Not effective for high / 24 hour building use
- May lead to higher internal temperatures than the equivalent lightweight buildings if internal gains are stored and not released through ventilation.
- May need mechanical ventilation to maximize effectiveness

Thermal mass overall has several limitations and may pose considerable design constraints however if it is used within appropriate conditions it can provide significant benefits in cooling a building.

3.3.3 Natural ventilation in an urban environment

The urban environment presents several challenges to the application of natural ventilation strategies such as, lower wind speeds, higher temperatures (due to the urban heat island effect), increased noise and pollution.

Santamouris et al., (2001) claim that the heat island effect reduces significantly (about 25%) the efficiency of air conditioning systems. This can lead to a further increase in overall size and use of A/C systems and thus intensify peak electricity demand and energy consumption for cooling purposes.

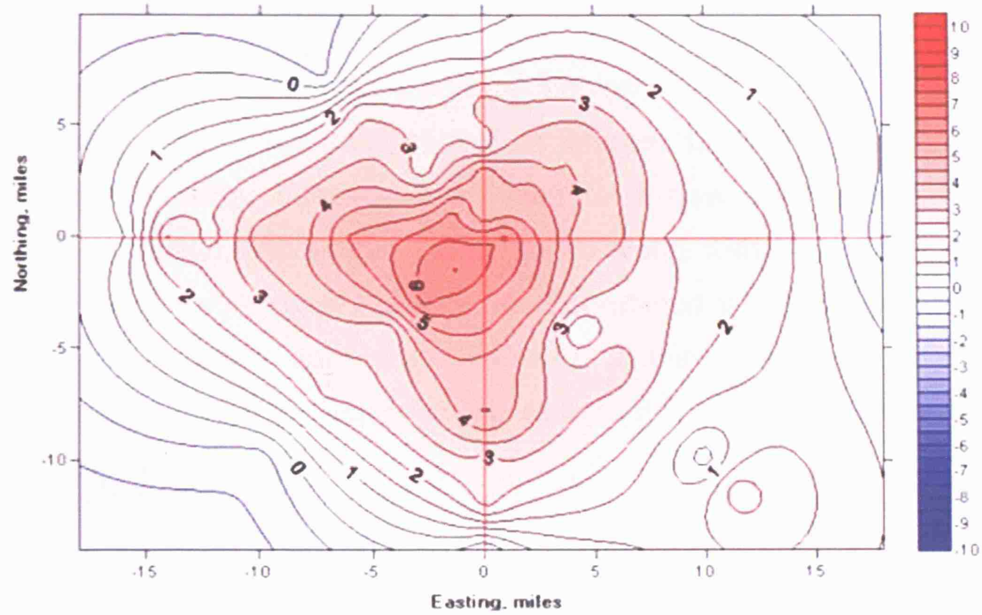


Figure 3.5.1: The variation in local heat island intensity (in K) across London on 2 August 1999 at 02:00 Source: Watkins et al., 2002

The urban heat island would also reduce the effectiveness of passive ventilation and in particular night ventilation because, according to Kolokotroni et al. (2005), the UHI was found to be a predominantly nocturnal phenomenon. According to the same scientists, increased urban temperatures (especially those during the night should be taken into account as they result in significant deviations from using standard meteorological weather data.

The urban environment has some beneficial aspects such as over shading. Based on experimental data and empirical modeling by Ghiaus et al. (2005) it was shown that air temperatures within urban canyons can be significantly lower than those sustained under basic shading canopies.

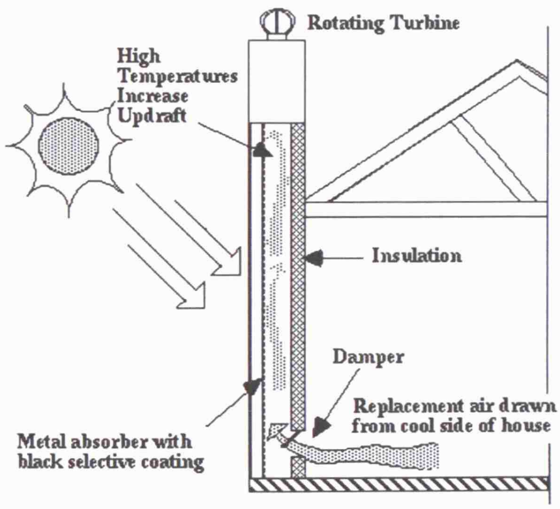
The impetus towards a bioclimatic architecture and increased pollution levels in cities highlight the importance of further investigating innovative strategies that can control the source, rate and quality of air introduced in naturally ventilated buildings.

4. Solar chimney: an environmental concept

For decades air conditioning and mechanical ventilation have been the standard method of environmental control in offices. Global warming, pollution and dwindling energy supplies have lead to a new environmental approach in building design. Innovative technologies along with bioclimatic principles and traditional design strategies are often combined to create new and potentially successful design solutions. The solar chimney is one of these concepts currently explored by scientists as well as designers; mostly through research and experimentation.

4.1 Introduction to solar chimney design

A simple description of a solar chimney, based on information found in related literature, is that of a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building.



Images 3, 4: Sketch concept of solar chimney design and solar chimneys at BRE offices
(Sources: Greenbuilder, 2005 and Feilden Clegg Bradley architects, 2005)

Solar chimneys, often mentioned as thermal chimneys, rely primarily on the principles of thermal buoyancy and the harnessing of solar energy to create and sustain stack driven ventilation. There are however many other parameters that can dramatically affect the performance of a solar chimney. These can be based on weather conditions such as wind speed, wind direction, shading conditions and variations in external temperature. Building design parameters such as internal heat gains, building fabric, shape, dimensions, orientation, and aperture size will also play an important role in the performance of a solar chimney.

The role of a solar chimney is to generate stack driven ventilation therefore, its primary design targets are to maximize and sustain the conditions that create stack effect which are temperature and pressure differences.

There are number of solar chimney variations. The basic design elements are:

- The solar collector area: This can be located in the top part of the chimney or can include the entire shaft. Orientation, type of glazing, insulation and thermal properties of this element are crucial for harnessing, retaining and utilizing solar gains
- The main ventilation shaft: The location, height, cross section and the thermal properties of this structure are also very important.
- The inlet and outlet air apertures: The size, location as well as aerodynamic aspects of these elements are very significant.

The use of a solar chimney may benefit natural ventilation and passive cooling strategies of buildings thus help reduce energy use, CO2 emissions and pollution in general. Some of the potential benefits regarding natural ventilation are:

- Improve ventilation rates on still, hot days
- Reduce reliance to wind and wind driven ventilation
- Improve control of air flow though a building
- Allow greater choice of air intake (i.e. leeward, shaded side of a building)
- Improve air quality and reduce noise levels in urban areas
- Increase night time ventilation rates
- Allow ventilation of narrow, small spaces with minimal exposure to external elements

Potential benefits regarding passive cooling may include:

- Improve passive cooling during warm season (mostly on still, hot days)

- Improve night cooling rates
- Enhance performance of thermal mass (cooling, cool storage)
- Improve thermal comfort (reduced air speeds, draughts)

In several research experiments and built precedents, solar chimneys are found in hybrid form, combined with various artificial means such as, low voltage fans and heated elements. Solar chimneys could also be used in winter conditions to preheat incoming air.

4.2 Case Study: BRE Offices, Garston, UK

The solar chimney is something of a chimera in the building industry: it is more often found and studied in design handbooks rather than actual buildings. There are however, several buildings that incorporate a number of solar chimney design principles. The British Research Establishment (BRE) office building in Garston, incorporates solar assisted passive ventilation stacks as part of its ventilation strategy.

Figure 4.1.1: Building Research Establishment offices, Garston
Source: Feilden Clegg Bradley architects, 2005

Designed by architects Feilden Clegg Bradley, the BRE offices aim to reduce energy consumption and CO_2 emissions by 30% from current best practice guidelines and sustain comfortable environmental conditions without the use of air conditioning. The passive ventilation stacks, solar shading, and hollow concrete slabs with embedded under floor cooling are key features of this building. Ventilation and heating systems are controlled by the building management system (BMS) while a degree of user override is provided to adjust conditions to occupants needs.

The building utilizes five vertical shafts as an integral part of the ventilation and cooling strategy. The main components of theses stacks are a south facing glass-block wall, thermal mass walls and stainless steel round exhausts rising a few meters above roof level. The chimneys are connected to the curved hollow concrete floor slabs which are cooled via night ventilation. Pipes embedded in the floor can provide additional cooling utilizing groundwater.

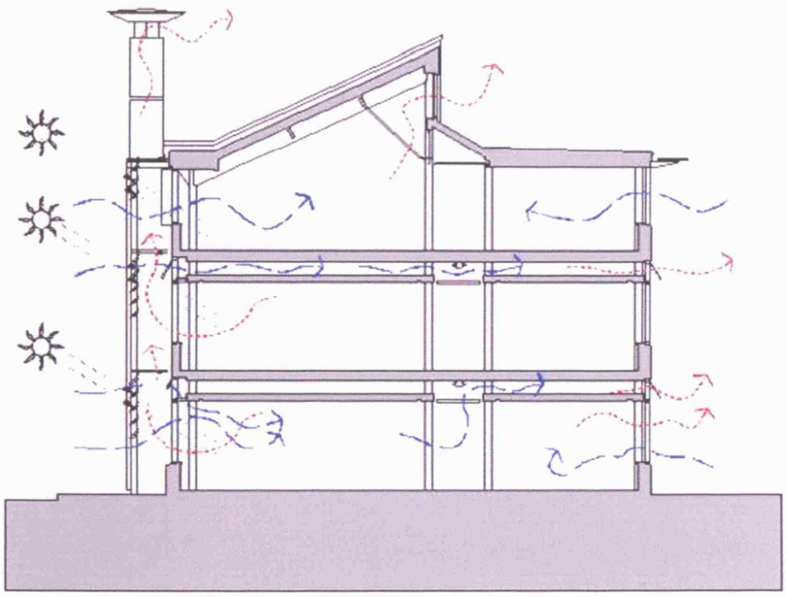


Image 5: Cross section showing air flow patterns through BRE building and image of passive ventilation stack Source: Feilden Clegg Bradley architects, 2005

On warm windy days air is drawn in through passages in the curved hollow concrete floor slabs. Stack ventilation naturally rising out through the stainless steel chimneys enhances the air flow through the building. The movement of air across the chimney tops enhances the stack effect.

During warm, still days, the building relies mostly on the stack effect while air is taken from the shady north side of the building. Low-energy fans in the tops of the stacks can also be used to improve airflow.

Overnight, control systems enable ventilation paths through the hollow concrete slab removing the heat stored during the day and storing 'coolth' for the following day. The exposed curved ceiling gives more surface area than a flat ceiling would, acting as a cool 'radiator', again providing summer cooling.

Research based on actual performance measurements of the passive stacks found that they enhance cooling and ventilation during warm and still days and may also have the potential to assist night-time cooling due to their use of thermal mass. (Ní Riain et al., 1999)

5. Literature review: aspects of solar chimney design

The potential role of solar chimneys in building ventilation and cooling was approached through a review of existing literature. The findings of this investigation are categorized in themes and establish the initial groundwork for creating the building simulation models that are used in further investigations.

5.1 Methods of existing research

There is a limited amount of experimentation considering chimney enhanced convection. (Fisher et al. 1999) Most scientific research on the subject is on smaller size solar chimneys suitable for ventilating and cooling large electrical and electronic systems – not buildings. The most common methods of researching the subject include physical modeling and numerical simulation. Computer simulation is generally limited, but advanced computers and new software are progressively introducing this approach in many areas of research and design applications.

5.2 Solar chimney design elements

This category includes scientific data and references relating specific design and construction elements of solar chimneys and their performance associated with their ability to increase ventilation and cooling.

5.2.1 Height

Chimney height is an important parameter that will affect temperature and pressure differences and thus the potential force of the stack effect. Alfonso et al. (2000) demonstrate that greater air flow rates and amplitude are sustained through a solar chimney with increased height yet this phenomenon is reduced as the height is increased further.

Aboulnaga et al. (2000) demonstrate that combining a wall shaft with a solar chimney on the roof of a building, effectively increasing the overall height of chimney, increases the induced flow rate and cooling load of a building. Ding et al. (2005) note that the height of a solar chimney connected to a double skin space influences the quantity of solar radiation absorbed by the thermal storage wall and stack effect occurring in the space, consequently increasing air change rate.

5.2.2 Length and width

Increasing the length of a solar chimney increases its exposure to solar gains. It also allows apertures to be elongated and placed at higher levels thus drawing air from a wide area closer to the ceiling where it is warmer. According to Alfonso et al. (2000) greater air flow rates and amplitude can be achieved through a solar chimney by increasing its length and cross section; this can be more effective than increasing the height.

Studies of the performance of a typical cavity used as a solar chimney on a full-scale house model under steady-state conditions by Bouchair (1994) demonstrated that air flow rate maximized when the cavity width was between 0.2 m and 0.3 m.

Balocco, (2002) demonstrates that air flow rate through a ventilated facade increases with the cavity width it was also shown that this effect is maximum when the cavity width is 20-30 cm.

For a specific building design there is an optimum cavity width in a solar chimney at which maximum ventilation flow rate can be achieved. The optimum cavity width, according to Spencer et al. (2000), is dependent on the chimney height, the size of the room inlet and the size of the solar chimney inlet. Comparisons between measured ventilation flow rates and numerical predictions suggested that theoretical models, which assume uniform temperature distribution across the chimney width, may in some cases over predict the chimney performance. The main reason sighted for this is the underestimation of the pressure losses at the chimney outlet by using loss coefficients obtained for normal forced flows.

5.2.3 Form and shape

Considerable natural ventilation can be generated by solar induced temperature difference in a tilted solar chimney structure. A study by Hamdy et al. (1998) showed that an angle of 60 degrees creates optimal performance for a tilted type solar chimney in Egypt. This analysis though was based on the effects of solar heat gain and excluded the effect of wind and fluid dynamics. Applying a similar strategy, Khedari et al. (1997) conducted experiments on pitched roofs designed as solar collectors in order to induce stack effect ventilation in small residential buildings. Their studies show that optimum roof pitch in Thailand would be 30 degrees.

Elmualim et al. (2002) investigate the relationship between air flow and the cross section shape of a chimney. They found that air flow for a rectangular chimney extract is much higher than that for a cylindrical for the same wind speed. It is speculated that the sharp edges of the square system create a larger region of flow separation and thus higher pressure difference across the device.

Chen et al. (2003) conducted experiments on an experimental solar chimney model with a variable gap-to-height ratio between 1:15 and 2:5 and different heat flux and inclination angles. Results showed that a maximum air flow rate was achieved at an inclination angle around 45 for a 200 mm gap and 1.5 m high chimney. The air flow rate for this configuration is about 45% higher than that for a vertical chimney at identical environmental conditions. The reason for this flow rate increase is shown to be due to the relatively even airspeed inside the chimney, which significantly reduces the pressure loss at the chimney inlet and outlet compared to the corresponding vertical chimney. For solar chimneys with large cross sections the temperature and air flow distribution becomes more unsteady and less predictable.

According to Balocco (2002), "geometry and rugosity of the channel within a ventilated facade affect uniformity and continuity of the heat flux, the surface temperature variation along the channel and the pressure losses.

Air flow discharge due to the stack effect occurring within the larger context of a typical residential stairwell was found to decrease as the inter zone temperature difference increased. (Peppes et al., 2000) This decrease was attributed to an increase in turbulence caused by mixing between the warmer rising flow and the cooler descending flow as the temperature differences increased.

5.2.4 Thermal mass

According to Alfonso et al. (2000) wall thickness does not change significantly the average flow rates of a solar chimney. However a thicker wall increases the thermal mass and thus the amount of energy stored within the chimney. This in effect decreases slightly the air flow rate during the day (sunny period) and increases it during the night (cool period). Therefore the wall thickness and in extent the utilization of the solar chimney's thermal mass can be used to control its diurnal performance. Thus a thin wall will optimize day time ventilation while a thicker wall will improve night time ventilation. In the same paper Alfonso et al. (2000) note that a wall thickness above 10 cm will not produce any significant differences in the diurnal performance of a solar chimney.

5.2.5 Insulation

The use of insulation reduces heat losses therefore it can increase daily as well as night flow rates. It has been demonstrated that in certain climate and type of solar chimney the lack of insulation can reduce the efficiency of ventilation considerably. (Alfonso et al., 2000)

LeMay et al. (1989) tested various types of exhaust chimneys in order to measure the effect of chimney insulation. It was found that from a cold start all chimneys formed a wall condensate but better insulated chimneys had shorter condensation periods and attained operating conditions much faster.

5.2.6 Glazing

The performance of a glazed solar chimney is influenced by the outdoor air conditions as well as wall solar heat gains. Single glazing is shown to be inadequate for solar chimneys due to possible condensation and downdraught in a cold winter. Even with double glazing, there still exist risks of condensation on the glass and downdraught in the chimney in a cold winter. Triple glazing for a solar chimney can reduce both risks of condensation and downdraught. (Gan et al., 1998)

5.2.7 Inlet and outlet apertures

Model measurements and CFD analysis of an eight floor office space with double skin structure connected to a solar chimney show that aperture area on every floor is a crucial factor in establishing adequate air flow and pressure for the stack effect and ventilation of each floor, especially the top floor. Increasing the area of the outlet apertures in the double skin/ thermal chimney construction may increase the ventilation rate in the lower floors but this effect will actually decrease with height so that in the upper floors of a multistory building the differences are negligible. (Ding et al., 2005)

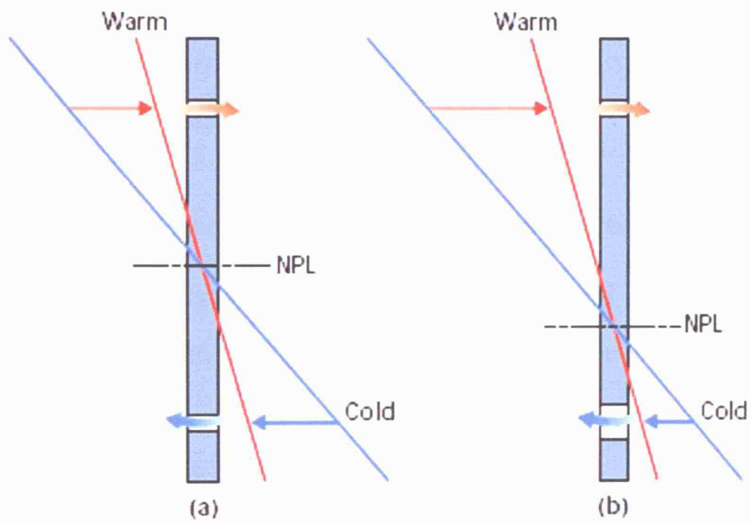


Figure 5.2.7 Impact of size of openings on neutral pressure level; openings of equal size, (b) openings unequal
Source: CIBSE AM10, p.12

In figure 5.2.7(a) area of openings in stack are equal thus in theory pressure across the apertures is also equal while the neutral pressure level (NPL) is half way. In figure 5.2.7(b) because the lower hole is bigger, its resistance to flow is lower than in the upper opening. According to the law of mass conservation the pressure drop across the lower opening must decrease, and that across the upper will increase until the flows equalize while the NPL is now at a lower point. In stack effect air will flow from the lower cold strata to the upper warm strata above the NPL. (CIBSE AM10)

Computer simulations by Gratia et al. (2004a), on a typical office building with a double skin facade and a solar chimney at the top demonstrated that the location and area of windows may dramatically affect stack effect and air flows. According to the same study increasing the size of the apertures located on the facade opposite the double skin facade and chimney improved considerably ventilation rates.

5.2.8 Orientation

Several studies mention that optimum solar gains increase the efficiency of a solar chimney yet there were no studies found specifically examining optimum orientation. Computer simulation of an office building in Belgium showed that summer cooling loads were considerably higher when the double skin facade was located on the south side of the building, as opposed to being on the north. (Gratia et al., 2004, a)

5.3 Weather Conditions and stack effect

Variations in temperature, wind speed and solar exposure caused by changing weather conditions will directly influence the operation of a solar chimney.

5.3.1 Wind related conditions

Bansal et al. (2004) studied a solar chimney-assisted wind tower for natural ventilation in buildings. The combination of wind tower and solar chimney enabled wind and buoyancy forces to be utilized to generate air flow in the building. The estimated effect of the solar chimney was shown to be substantial in promoting natural ventilation for low wind speeds.

Gan et al. (1998) state that an effective way to take advantage of prevailing wind forces is to locate the chimney exhaust opening in a region of negative wind pressure and the building intake openings in a region of positive pressure
Wind and stack force will often counter each other, depending on many parameters such as wind speed, building orientation, aperture location and even local planning conditions. During a sunny day the zone air change rate in a south facing double-skin will fluctuate according to wind intensity and direction. For a north facing double-skin facade during night time ventilation, the wind will often determine ventilation rates and even air flow direction. (Gratia et al., 2004c)

Wind velocity and direction in conjunction with the sizes of openings can affect the air change rates in stack effect. (Delgado et al., 1996) An effective measure to take advantage of prevailing wind forces is to install the chimney exhaust opening in a region of negative wind pressure and intake openings in a region of positive pressure. (Gan et al., 1998)

5.3.2 Seasonal climate changes

The effect of solar energy assistance is examined by Alfonso et al. (2000) by comparing the air flow rates for a solar and a conventional chimney. Flow rates with solar assistance are always higher and the difference is more significant during sunshine hours. They further conclude that daily amplitude in air flow rate is smaller with the solar chimney and generally the solar effect is greater in warm/sunny months.

Stack effect during hot season is not as pronounced as in cold season since pressure differences during summer are usually much smaller due to lower temperature differences. In tall buildings during a cold winter peak stack forces can be twice as great as those occurring during hot summer. (Lovatt et al. 1994)

5.4 General findings

This category includes a range of scientific data and references relating to design aspects that could indirectly influence solar chimney design and function.

5.4.1 Stack Flow: Heat assisted / recovered

Kazansky et al. (2003) employed a heated plate within a chimney and through physical experiments and numerical simulations confirmed that this can enhance considerably the air flow rate created by the stack effect. In the same experiments it was found that air flow rate increased with chimney height.

Modifications in a passive stack, such as pipes for heat recovery, were evaluated using tests and computational fluid dynamics (CFD) by Shao et al (1997) According to this study for an heat recovery efficiency of 50% and a stack flow speed of 0.5 m/s, the pressure loss within the stack and pipe assembly was about 1 Pa. Heat pipes located at the bottom or towards the center of the stack create greater air flow loss than those located at the top or close to the stack walls. Pressure losses could be further minimized by using streamlined heat pipes.

5.4.2 Trombe wall and passive cooling

Research findings regarding Trombe walls proved quite relevant to solar chimney design and provided some useful points for consideration:

"When a Trombe wall is used for summer cooling, the ventilation rate induced by the buoyancy effect increases with the wall temperature, solar heat gain, wall height and thickness. Provided that the dimensions of the inlet and outlet openings increase with channel width the ventilation rate also increases with the distance between the wall and glazing. The use of double glazing instead of single glazing for a Trombe wall system not only reduces heat losses in winter hut also enhances passive cooling in summer. To maximize the ventilation rate for summer cooling the interior surface of the storage wall should be insulated. This also prevents undesirable overheating of room air due to convection and radiation heat transfer from the wall." (Gan, 1998)

5.4.3 Stack ventilation and building apertures

The location of any apertures on the building envelope will change the location of the neutral pressure level (NPL) and this may often result in dramatic changes in air flow rates and even direction. In high buildings dependent on stack ventilation fresh air flow will be considerably inhibited through apertures placed above the NPL. Therefore at the highest building level the exhaust opening should be placed well above this level and be made as large as possible. Locating the exhaust aperture on the leeside of the building will increase stack pressure air flows and avoid backflows from direct wind forces. (Flourentzou et al., 1998)

Physical measurements of a mock model in Thailand show that an optimum combination of natural ventilation via windows with the stack effect created by a solar chimney can improve air flow through a single story building and help reduce the indoor temperature. (Khedari et al., 2000)

Improved air-tightness in newer residential buildings with typical stack ventilation shafts decreases air movement and increases the possibility of chimney back-draughts, particularly in mild weather when the stack effect is modest. (Dumont et al., 1990)

5.4.4 Preconditioning air intake for cooling

Solar chimneys can be used to create ventilation through spaces inaccessible to wind. According to Santamouris et al. (1996), pre-cooled air, circulated through underground labyrinths or buried pipes, may be drawn inside a building with the help of a solar chimney.

5.5 Design Feedback

Review of existing literature revealed a limited amount of research related directly to solar chimneys; a considerable part of this was based on subjects with different scope such as double skin facades, passive ventilation shafts or simple exhaust stacks. The majority of research focused mostly on the potential for improving air flows rather than cooling. Table 5.1 provides an overview of parameters affecting solar chimney performance.

Table 5.1 Literature review: Summary on solar chimney design

	Parameter	Modification	Comments
Solar chimney design elements	Height	Increase	Greater air flows and cooling potential Phenomenon reduced past certain height
	Length / width	Increase	Greater solar gains, improved airflow, Allows optimizing chimney apertures
	Cross section	Increase	Improved air flow but may cause turbulence/ backflow. Reduced cross section areas may be more effective
	Form/ shape	Rectangular/ Round	Rectangular shaped chimneys seem to improve airflow in conjunction with wind
		Sloped Stack	May improve air flow in some cases
	Thermal mass	Increase	Allows control of diurnal performance: Improves night time air flows and reduces day time flows.
	Insulation	Improve	Minimizes heat losses, improves air flow. Also prevents heat gains in building.
	Glazing	Optimize U-Value	Allows max. solar gains, minimizes heat losses, improves air flow.
	Outlet aperture	Increase	May increase airflow
	Inlet aperture	Increase	Reduces pressure at inflow
	Orientation	South	Increases solar gains and air flows
Weather	Wind related conditions	Exposure	Wind may reinforce flow if air inlets are on windward side of building and outlet on leeward. May cause backflow.
	Seasons	Warm / Cold	Warm, sunny weather improves solar gains and air effect. Cold weather increases stack pressure differences but may cause back flows in chimneys
General issues	Heat assisted	Improve heat gains	Heat gains either solar, building related or induced will improve air flow
	Heat recovery	Introduce pipe work	Obstacles within the shaft will reduce air flow. Effect may be minimized if elements located near shaft wall or towards the top.
	Building apertures	Orientation	Combined with wind direction may enhance or restrict performance. Opening on windward side of building will improve stack effect.
		Size, location	Affect NPL and stack effect
	Restricted areas	Raised floors, Suspended ceilings, voids	Stack induced ventilation may help ventilate spaces restricted to external access, winds

The potential for improved ventilation rates seems more evident than those for cooling but the reliance and vulnerability of solar chimneys to external conditions, especially wind, may still pose difficult challenges. The lack of specific typologies strongly suggests investigation of several modifications and simulation models. Minimizing the number of modifications per case and examining simulation data for different time periods seems necessary. An assessment of diurnal fluctuations in temperatures and ventilation rates will provide a good indication of night cooling performance.

In general, the review of existing research helped identify several key aspects of solar chimneys and began to suggest several configurations for investigation with building simulation.

6. Building Simulation Research

Computer simulation technology is a growing area in building development and research. New commercial applications are progressively becoming available in the building industry market. A growing number of architects and engineers use computer modeling to test ideas in their effort to improve design and environmental performance.

6.1 Simulation Program: TAS Building Designer

TAS is a powerful building simulation program that uses thermodynamic laws to simulate a number of physical parameters such as heat transfer, temperature, and air flow. Problems are simulated geometrically using 2D Plate, 3D Brick and Tetrahedron elements. TAS uses a Finite Element method to convert geometry into an accurate resistor / capacitor representation which is then accurately and quickly solved using a finite difference method. (EDSL, 2005)

TAS Building designer is being used by professionals and scientists with considerable success. However within the current research scope it has some important limitations which include:

- Building form: Curves may not be represented or simulated in TAS
- Aerodynamic / fluid dynamic: TAS is not a CFD program therefore it will not be able to represent many of the effects of wind, wind turbulence, etc.
- It is not possible, within the context of this research to simulate specific variations in microclimate such as the cool air from the shaded/ north side of a building. This is a significant limitation in the characteristic capacity of a solar chimney to introduce air in a building via advantageous locations.

6.3 Simulation strategy

Identifying early on solar chimney dynamics and some of the environmental conditions that influence performance is important in setting up a simulation strategy and allow an efficient comparison of results.

6.2.1 Examined Parameters

The research is focused on natural ventilation and cooling therefore the internal environmental parameters examined are:

- Dry Bulb Temperature (C°): Provides a simple and easy assessment of thermal conditions and cooling.
- Resultant Temperature (C°): Relates to thermal comfort and shows the effects of thermal mass.
- Air Flows (kg/s): The amount of air moving though the building models, effectively the ventilation rate.
- Solar Gains (W): In some instances the use of a solar chimney increases gains and thus this becomes useful for some comparisons.

The types of air flows examined and the respective conventions used to define them are the following:

- Cross Ventilation: This type of air flow refers to wind driven ventilation; typically the air flows (outflows) through the apertures of the main office floors or in some cases the sub floors. A small percentage of cross ventilation is created by local stack effect but for the purposes of this research this is not crucial.
- Stack Ventilation: This type of ventilation refers to the actual stack effect occurring in the solar chimney. It is typically assessed by calculating the air flow (out flow) through the top chimney aperture or alternatively the air flowing in through the internal chimney apertures.
- Back Flows: This term is used to refer to chimney air flows that in some instances occur in the opposite direction of the natural stack effect. This is used to examine the efficiency of the solar chimney or the effects of wind and negative pressure.
- Total Ventilation: This is the total amount of air going through a building/model and is typically represented by the sum of cross and stack ventilation.
- Diurnal air flow rates: Daytime and Night time ventilation

6.2.2 General assumptions

For the purposes of this research the daytime and night time periods are associated with the assigned building schedules and are from 09:00 to 18:00 for the former and 18:00 to 09:00 for the latter. Basically these schedules coincide with the hours of building use and occupancy. Another convention used to simplify model comparison is that occupancy and consequently internal gains schedules remain the same on a daily basis. In real conditions reduced building use, for example during weekends, would have allowed the building fabric to discard some extra heat gains. The focus on solar chimney design and need to limit variables for comparison purposes deemed more important to keep a steady use pattern. Basic calculations were used to select an appropriate building aperture opening that would maintain air flow rates and velocity within recommended comfort conditions. (Appendix 1, page 86)

6.2.2 Simulation periods

Building simulation with TAS was performed in two distinct time periods:

- 24 hour period (Day 160): This method of simulation provided feedback on the diurnal performance of the building models and enabled the comparison of models on specific environmental conditions. It also allowed a detailed examination and understanding of model performance.

- 5 month period (Days 120-270): Assessment of performance over entire cooling season time provides more accurate results and may help identify performance patterns

6.2.3 Outline of investigations

Based on preliminary findings through literature review (Table 5.1) there are 13 investigations on solar chimney design presented in this report. Table 6.1 provides a brief description of these investigations, the computer simulation models used and their modifications.

Table 6.1 : Outline of investigations and computer simulation models

Investigations		Models	Description / Modification
1	Introducing a solar chimney	Model 0	Base case, cross ventilated office
		Model 1	Model 0 + solar chimney (> stack effect)
2	No wind, still day	Model 0S	Model 0, sheltered
		Model 1S	Model 1, sheltered
3	Reduce width, solar exposure	Model 1B	Model 1, 25% < width, chimney apertures
		Model 1C	Model 1, 50% < width , chim. Apertures
4	50% increase top chimney aperture	Model 1	Basic solar chimney model
		Model 3	Model 1, > 50% top chimney outlet
5	Chimney outlet orientation	Model 1	Basic solar chimney model (North)
		Model 4	Model 1, south, (prevailing wind)
6	Increase chimney height, stack effect	Model 1	Basic solar chimney model (6m)
		Model 5A	Model 1> 50% chimney height (9m)
		Model 5B	Model 1> 100% chimney height (12m)
7	2 top chimney outlets,1 North and 1 South	Model 1	Basic solar chimney model (North)
		Model 6	Model 1 + south aperture
		Model 6S	Model 6, sheltered (still day)
8	Increase chimney insulation	Model 1	Basic solar chimney model (50mm)
		Model 7	Model , insulation: 200mm
9	Sloped chimney top, improve flow	Model 1	Basic solar chimney model, flat top
		Model 8	Model 1, sloped top, aperture location
10	Increase chimney absorptance	Model 1	Basic solar chimney model, (α:0,4)
		Model 9	Model1 > absorptance (α:0,9)
11	Central chimney location, reduce solar gains	Model 1	Basic solar chimney model, (max sun)
		Model 10	Model 1, only top part exposed to sun
		Model 10B	Model 10 > 50% top chimney outlet
12	Increase thermal mass, store coolth, night cooling	Model 0B	Model 0 + double concrete floors
		Model 12	Mode 1, double concrete floor
		Model 13	Model 12 > thermal mass (concrete fins)
13	Chimney location + thermal mass	Mode 13	Best case thermal mass model
		Model 15	Model 13 +Model 10 combined

6.4 Building simulation models

6.4.1 Model 0: Base case

Model 0 is the basic simulation model. The modest layout helps simplify the simulation process by accommodating each modification with minimal interference thus allowing reasonable comparisons. Figures 6.1, 6.2 and Table 6.1 provide a comprehensive description and simulation parameters.

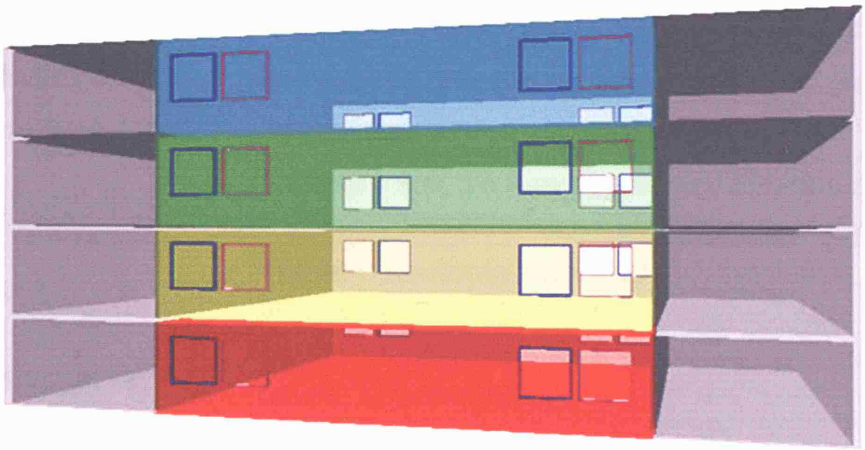


Figure 6.1 Model 0 (Base Case), 3D View

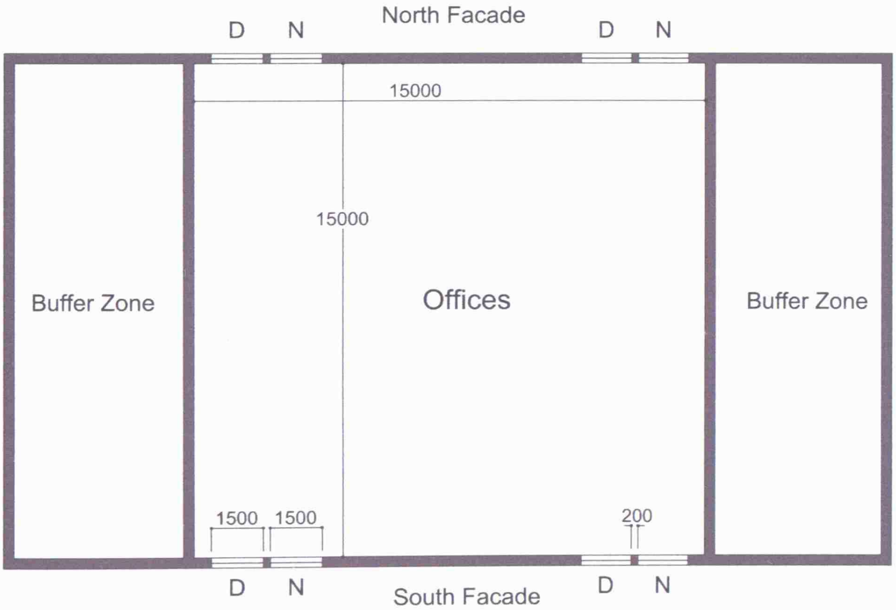


Figure 6.2 Model 0 (Base Case), Plan (dimensions in mm)

Table 6.1: Model 0S / Model 0S[1] / Model 0B[2] - Building simulation data				
Weather File UK KEW 76		**Simulation Day / Season** 160 / 120 -270		
Floors	4	**Dimensions**	15 length x15 width x 3 height	
Floor Area	225m²	**Volume**	675 m³	
Apertures	4 per floor, 1.5m x 1.5 m (gross per aperture), 1m above			
Day time	3.92 m²	**Night time**	3.92 m² (net area)	
Building elements				
Floors/Ceiling	150 mm concrete slab, 50 mm concrete screed, 10 mm tile			
Glazing	6mm low E, 12 mm air gap, 6 mm clear glass			
Aperture frame	25 mm wood			
Ground floor	1000mm soil, 75 mm aggregate, 150 mm concrete slab, 50 mm concrete screed, 5 mm tile			
Roof	150 mm concrete slab, 150 mm insulation, 50 mm concrete screed, 3 mm asphalt			
External Wall	25 mm plaster, 100 concrete block, 100 insulation, 50 mm cavity, 105 mm brick			
Internal Conditions				
Zones 4 main zones / 1 per floor				
Infiltration rate	0.3 ACH	Equipment sensible gains	15 W/m²	
Lighting gains	12 W/m²	Occupancy latent gains	5 W/m²	
Occupancy sensible gains		10 W/m²		
Schedules				
Internal conditions (Office hours): 09:00 – 18:00				
Day time ventilation: 09:00 – 18:00		**Night time ventilation**: 18:00 – 09:0		
Aperture Operation				
Day time	Open 50% at 19°C, shut at 18 °C, or wind speed > 10 m/s			
Night time	Open 50% at 16°C, shut at 15 °C, or wind speed > 10 m/s			
[1] Model 0S is Model 0 modelled under sheltered / no wind conditions				
[2] Model 0B is Model 0 but with double floor construction (0.6 m depth)				

Building model dimensions relate to typical office modules. The 15m width is based on rule of thumb regarding the maximum recommended dimension for efficient cross ventilation in a space with a 3m height. At this condition the use of a solar chimney could enhance existing cross ventilation and allow a reasonable comparison between stack driven and wind driven air flows.

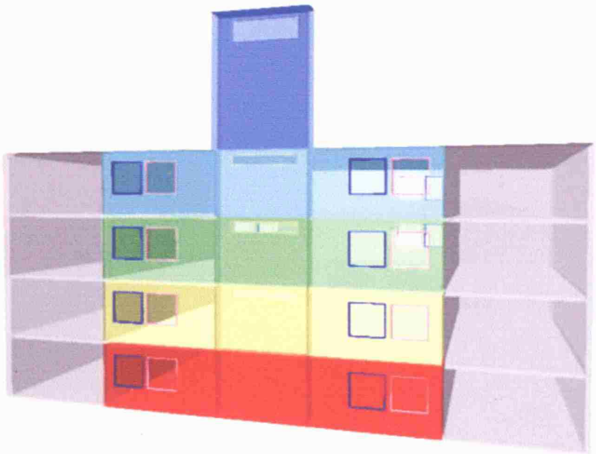
The fenestration area is generally limited in an effort to remain constant throughout the various model modifications and comparable in aperture size to the amount of openings introduced via the solar chimney. (Calculations and assumptions relating to main building apertures can be found in Appendix 1, p.86)

There are two types of windows located on each of the exposed facades; they are identical in size and remain constant in all models. These are day-time and night-time ventilation windows and are operated during the day and night respectively. Overall glazing area is limited for model simplification therefore, no shading devices are used in these windows.

6.4.2 Model 1: Basic solar chimney

Model 1 was created by modifying Model 0 and is the basic solar chimney model. Features of solar chimney design were based on previous research findings (Table 5.1). The chimney is located on the south facade of the building and extends two stories above roof level. It comprises of a south facing glass wall to maximise solar gains and the internal partition is made from insulated double leaf masonry wall in order to minimize solar gains into the office spaces yet deploy adequate thermal mass. The internal apertures of the solar chimney have interpane shading in order to avoid additional solar gains. These apertures are located close to ceiling level connecting the solar chimney shaft with each office space. An aperture located at the top, north side of the chimney links to the outside. Figure 6.3 shows the basic layout and dimensions of Model 1

Model 1 / Model 2



Base Case	Model 0
Feature	
Solar chimney	
A solar chimney is introduced in the base case (Model 0) to introduce stack driven ventilation.	

Modified Elements	Modifications
Introducing solar chimney	4m x 0.5m x 18m (internal shaft dimensions
Chimney internal wall partition (double leaf construction)	25mm plaster, 100mm block, 50mm air gap, 100mm insulation, 105 brick
Internal chimney apertures	1 per floor; 3m x 0..5 m; sill height 2.3
Chimney int. aperture shading	Mid pane blind (Solar transmittance: 0.038)
Chimney top aperture	3 m x 1 m at 4.8 m above roof
Chimney aperture schedules	Open continuously; 100% opening

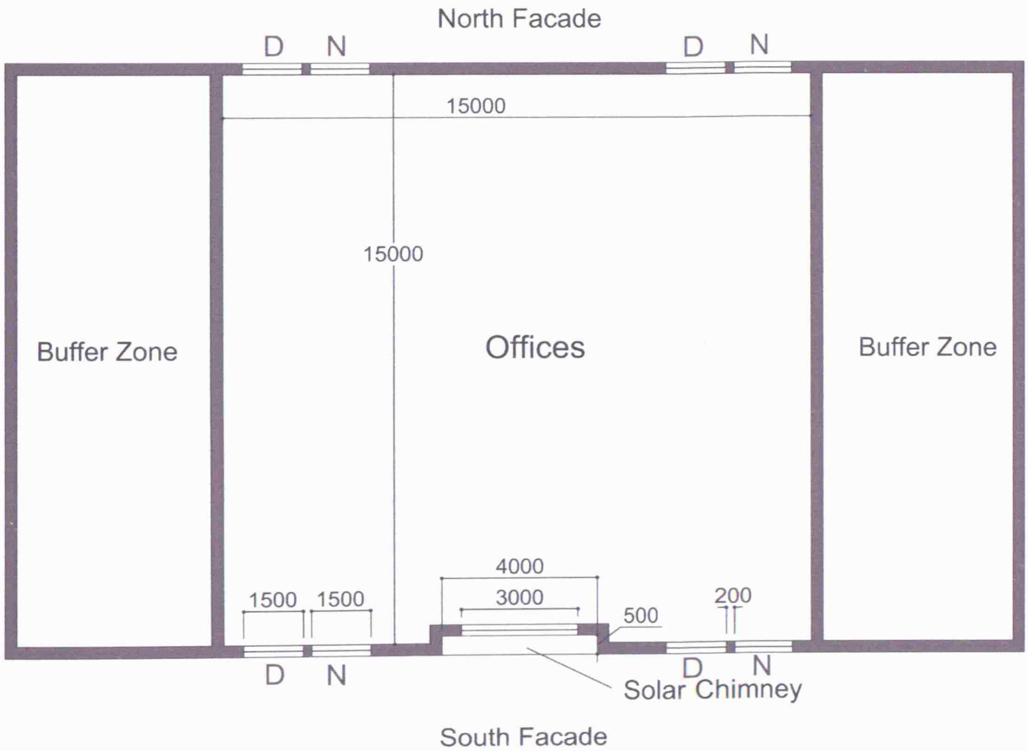
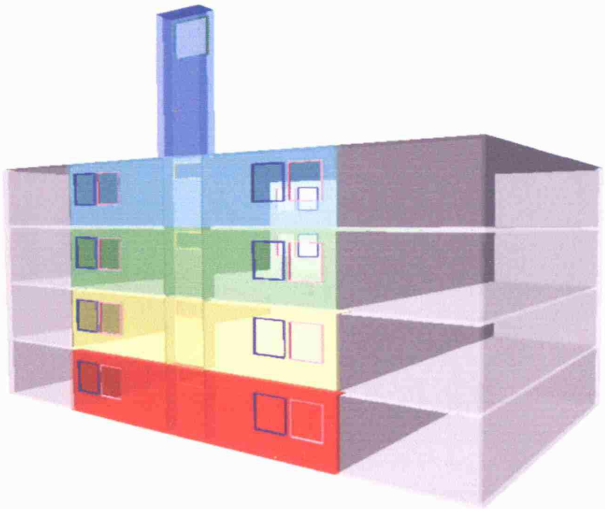


Figure 6.3 Model 1 (Basic solar chimney model); Plan (dimensions in mm)

6.4.3 Model Modifications

Model 1C

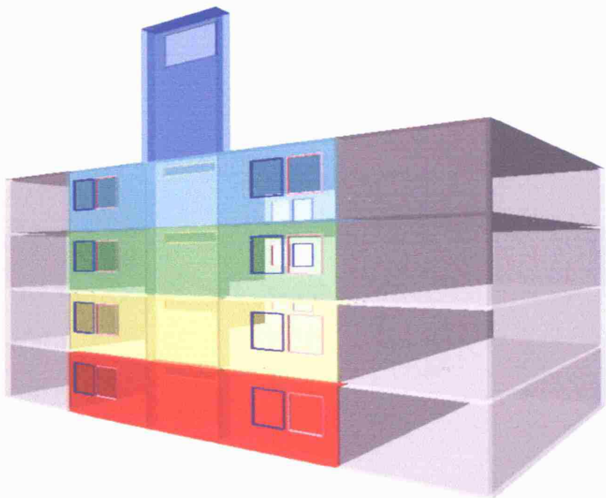


Base Case	Model 1
Features	
100% < chimney width	

Reduction of chimney width effectively reduces solar exposure and the cross section of the chimney. Chimney aperture dimensions change in order to keep opening area same. This reduces the effective stack height.

Modified Elements	**Modifications**
Chimney width	2 m
Internal chimney apertures	2 m x 0.75 m
Chimney top aperture	1.875 m x 1.6 m

Model 3

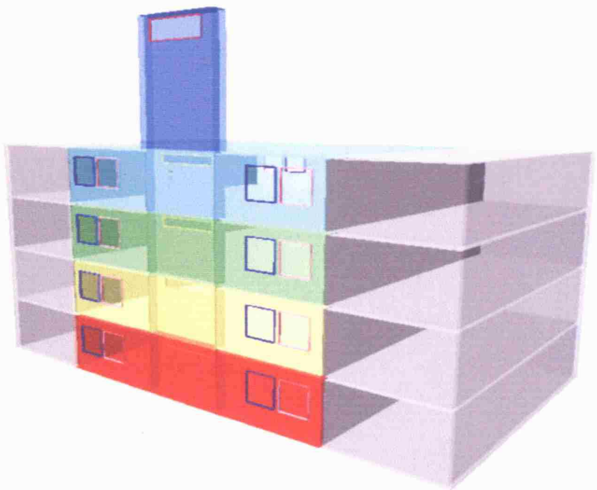


Base Case	Model 1
Feature	

50% increase in top chimney aperture. The NPL is expected to change. All other parameters remain the same.

Modified Elements	**Modifications**
Chimney top aperture	3 m x 1.5 m

Model 4

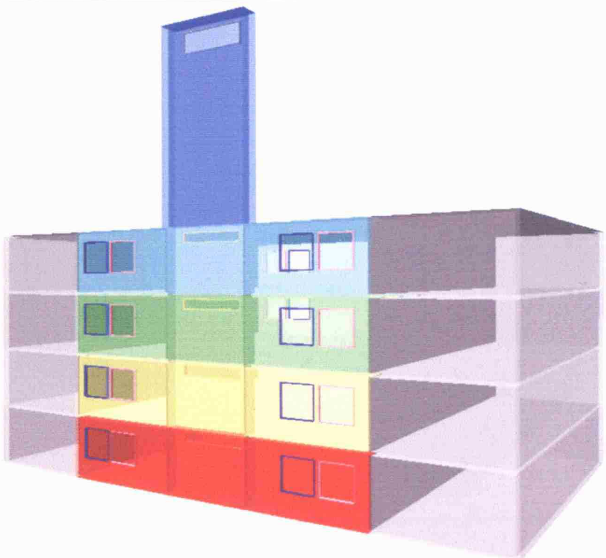


Base Case	Model 1
Feature	Top chimney aperture orientation

Prevailing winds in the UK (and during simulation DAY 160 in the KEW 76 weather file) are from the south / southwest direction. Locating the top chimney aperture on the south side of the solar chimney is effectively placing it on the windward side of the building.

Modified elements	**Modifications**
Chimney top aperture	South orientation

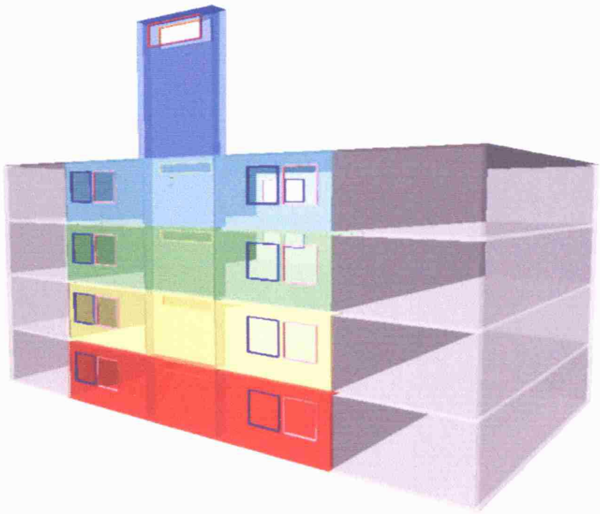
Model 5A / Model 5B

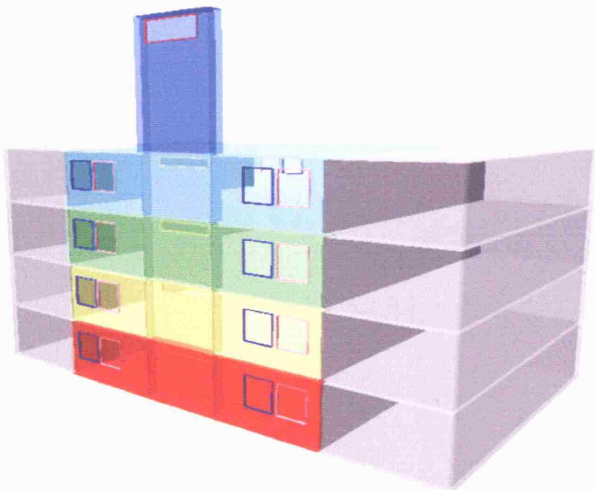


Base Case	Model 1
Feature	Solar Chimney height

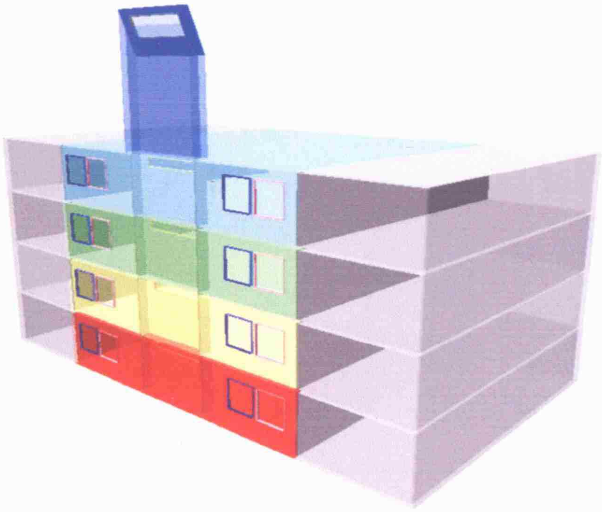
Changing the chimney height effectively alters the pressure coefficients and temperatures that create the stack effect. Exposure to the elements (wind, sun) will also vary.

Modified elements	**Modifications**
Chimney height	9m (Model A) and 12m (Model 5B)

Model 6 / Model 6S*		
	**Base Case**	Model 1
	Feature	Dual top chimney apertures
	Two top chimney apertures on the north and south the leeward and windward sides of the building respectively will expose the chimney air flows to prevailing winds. Investigate if this will help or disrupt the stack effect. The NPL will also change due to the increased aperture area.	
Modified elements	**Modifications**	
Chimney top apertures	2 apertures (North+ South) of equal area ($3m^2$)	
*Model 6S is Model 6 modelled under sheltered / no wind conditions		

Model 7		
	**Base Case**	Model 1
	Feature	>chimney insulation 200%
	Increasing the insulation in the chimney shaft from 50mm (100mm in the external part) to 200mm overall will reduce solar gains into the building. This will also help retain heat during cool periods and thus reinforce night time stack effect.	
Modified elements	**Modifications**	
Chimney shaft	**Increase insulation thickness to 200mm**	

Model 8

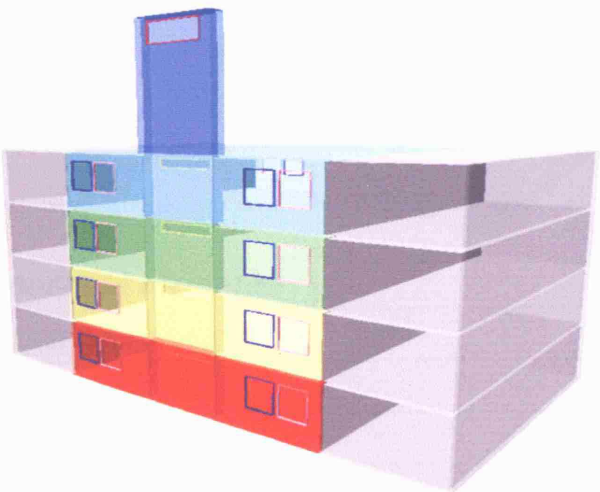


Base Case	Model 1
Feature	Sloped chimney top

Creating a slope on the top part of chimney and locating the exhaust aperture effectively increases slightly the chimney height and may also improve air flow by reducing friction coefficients

Modified elements	**Modifications**
Chimney top	Create slope ~ 60°, aperture location

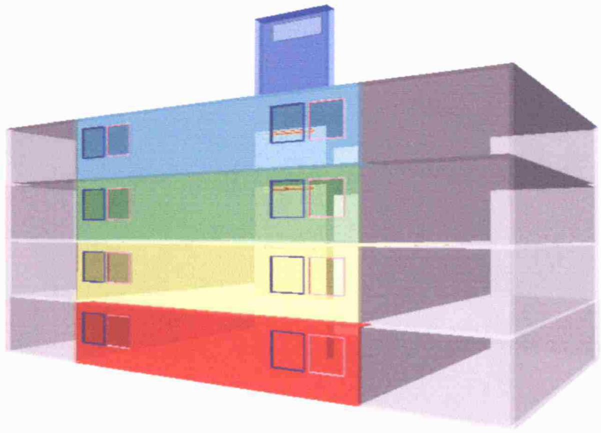
Model 9

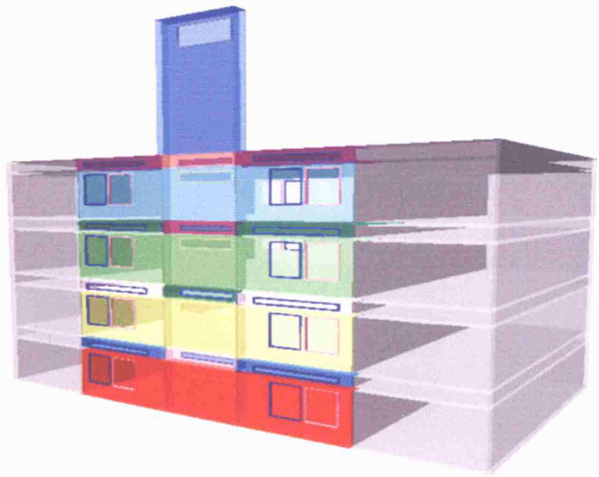


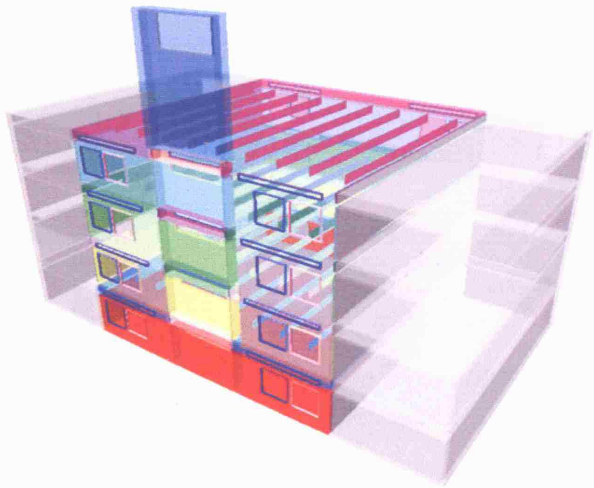
Base Case	Model 1
Feature	Increase chimney absorptance

Increasing the solar absorptance of the chimney shaft will increase solar gains, therefore temperatures and stack effect. This is achieved in simulation by adding black paint on the internal surface of chimney shaft.

Modified elements	**Modifications**
Chimney shaft	Increase absorptance (α:0,9)

<table>
<tr><td colspan="3">Model 10 / Model 10B*</td></tr>
<tr><td rowspan="3"></td><td>Base Case</td><td>Model 1</td></tr>
<tr><td>Feature</td><td>Central chimney location</td></tr>
<tr><td colspan="2">A chimney located within the building will have reduced solar exposure. This will affect stack effect and minimise solar gains in the building. Air flow patterns within building may change. Internal chimney apertures are doubled on each side (north/south) but total opening areas remain same.</td></tr>
<tr><td>Modified elements</td><td colspan="2">Modifications</td></tr>
<tr><td>Chimney location</td><td colspan="2">Locate chimney in building centre</td></tr>
<tr><td colspan="3">*In Model 10B internal chimney apertures are doubled in area. (2x 3mx0.5m)</td></tr>
</table>

<table>
<tr><td colspan="3">Model 12 / Model 0B[1]</td></tr>
<tr><td rowspan="3"></td><td>Base Case</td><td>Model 1 + Model 0B</td></tr>
<tr><td>Feature</td><td>Introduce double floors</td></tr>
<tr><td colspan="2">This will enhance the thermal mass. Double floors are located within existing floor space to keep building height same. External floor vents and internal chimney apertures are operated only during the night to cool structure and store coolth.</td></tr>
<tr><td>Modified elements</td><td colspan="2">Modifications</td></tr>
<tr><td>Main floors height</td><td colspan="2">Reduced to 2.4m</td></tr>
<tr><td>Windows</td><td colspan="2">Sill height reduced to 0.7m</td></tr>
<tr><td>Double floor</td><td colspan="2">Height: 0.6m</td></tr>
<tr><td>External floor vents*</td><td colspan="2">4 per sub floor; 4m x 0.3 m each</td></tr>
<tr><td>Chimney floor vents*</td><td colspan="2">1 per sub floor; 3m x0.3m each</td></tr>
<tr><td colspan="3">* Basic night time operating schedule
1 Model 0B based on Model 0 (Base Case) and is used for comparison with Model 12, has the same double floor arrangement but without the solar chimney</td></tr>
</table>

Model 13		
	**Base Case**	Model 12
	Feature	
	Increase further thermal mass	
	Concrete partitions are introduced within the double floor structure to enhance thermal mass. All other parameters remain same.	
Modified elements	**Modifications**	
Concrete partitions	11 per sub floor :11m x 0.6m x0.2m	

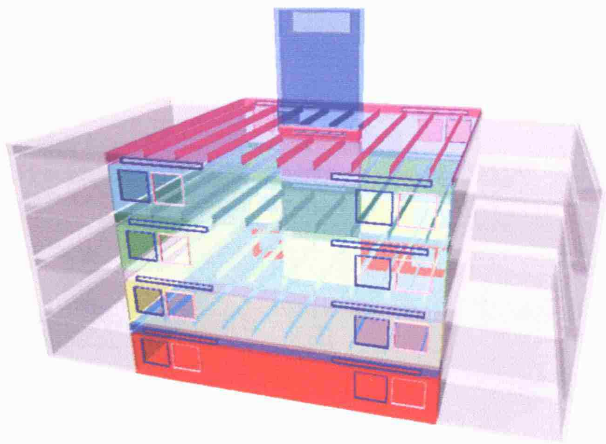
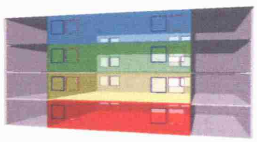
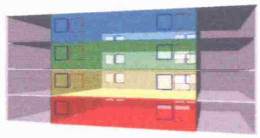
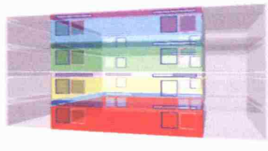
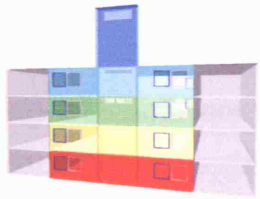
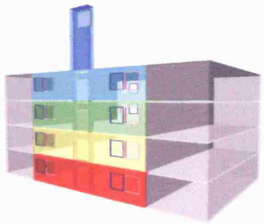
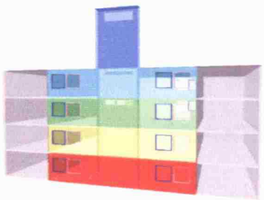
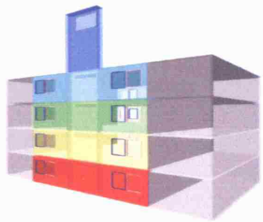
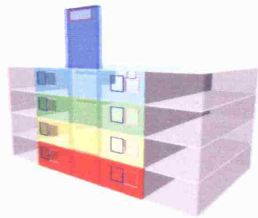
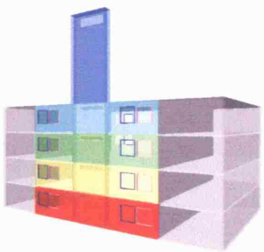
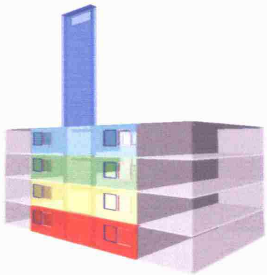
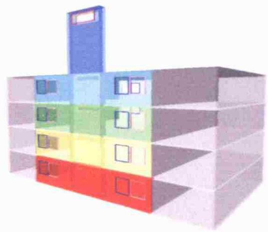
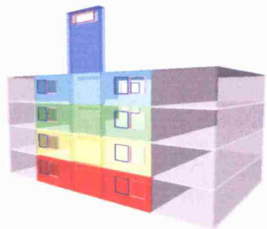
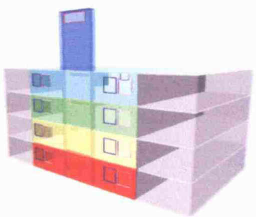
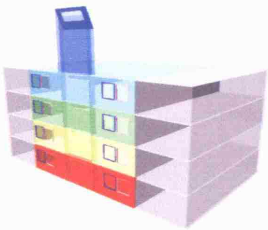
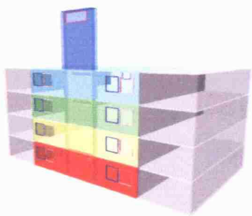
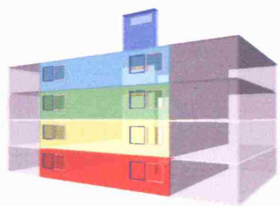
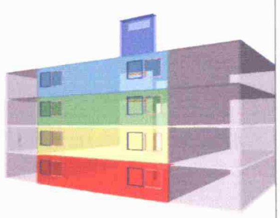
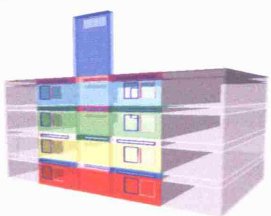
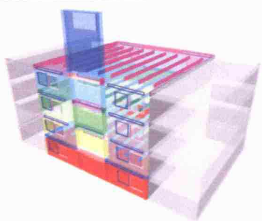
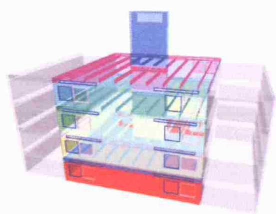
Model 15		
	**Base Case**	Model 10 + Model 13
	Feature	
	Combining thermal mass and central chimney location	
	This solution integrates the improved thermal mass conditions of Model 13 with the minimal solar gains offered by Model 10. All other parameters remain the same.	

Table 5.3: Simulation Models - Overview

			
Model 0 Base Model	**Model 0S** M0 Sheltered	**Model 0B** M0 double floors	**Model 1** M0 + solar chimney
			
Model 1C M1 < Width 100%	**Model 2** M1 sheltered	**Model 3** M1 > top aperture	**Model 4** M1 top ap. Orientation
			
Model 5A M1 > chimney height 50%	**Model 5B** M1 > chimney height 100%	**Model 6** 2 top apertures (N&S)	**Model 6S** Model 6 sheltered
			
Model 7 M1 + chimney insulation	**Model 8** sloped chimney top	**Model 9** M1 > absorptance	**Model 10** center location
			
Model 10B Model 10 > internal chimney apertures	**Model 12** M1 + double floors	**Model 13** M12 > thermal mass	**Model 15** M10 + M13 combined

7. Simulation Results

7.1 Simulation period: Day 160

Simulations are initially performed on a 24 hour period allowing TAS software to compute maximum data output. Simulation data for individual building models are compared in specific weather conditions and provide better understanding of performance characteristics. Results are presented in this chapter in a concise format. Further graphs and data are available in Appendix 2 (pages 87-114). DAY 160 from the TAS weather file KEW 76 was used for the simulations. Figure 7.1 and Table 7.1 provide further information on the prevailing conditions of this day.

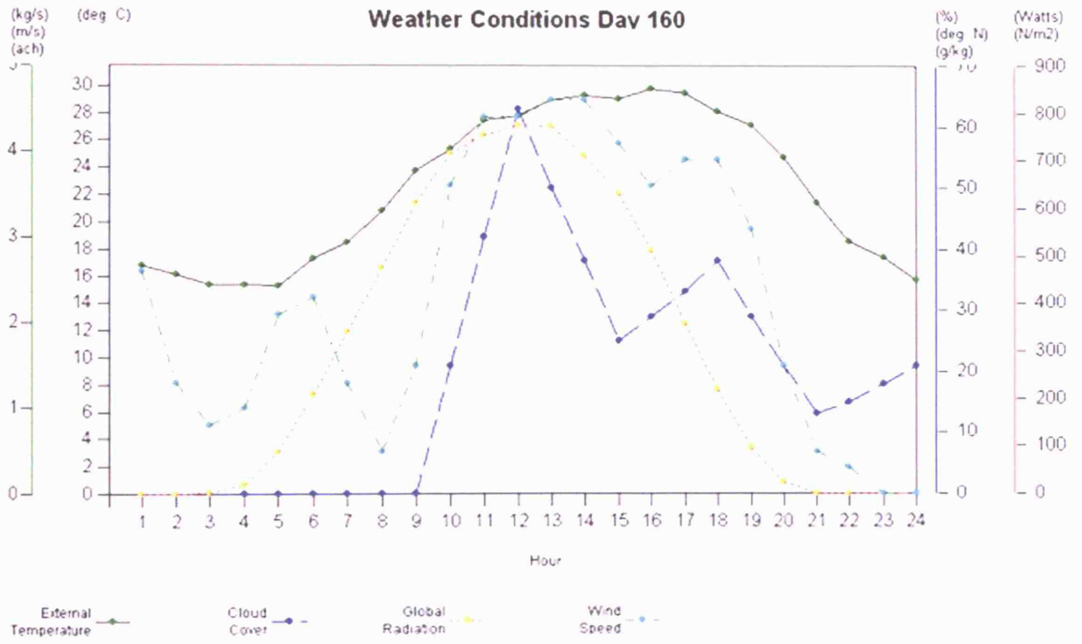


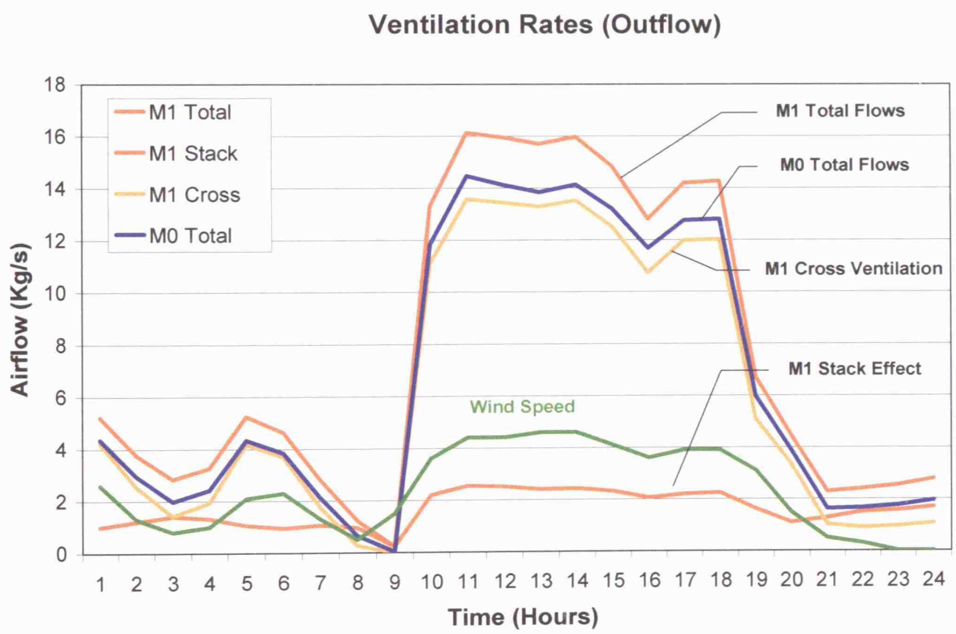
Figure 7.1 TAS screen capture of weather data for Day 160, KEW 76 weather file

Table 7.1 DAY 160: Basic weather data from KEW 76 weather file	
Maximum Dry Bulb Temperature	29.8 C°
Minimum Dry Bulb Temperature	15.3 C°
Maximum Wind Speed	4.6 m/s
Minimum Wind	0m/s
Global Radiation	775W/m²
Prevailing Winds	South / South West

7.1.1 Introducing a solar chimney

Investigation 1	
Simulation models	**Description / Features**
Model 0	Base case, cross ventilated office
Model 1	Model 0 + solar chimney (> stack effect)
Simulation Results	

- Very small reduction in dry bulb temperatures
- Temperature differences are greater during the night
- Increased total air flows but reduced cross ventilation
- Day time stack ventilation is about 20% of cross ventilation
- Night time stack is about 40-45% of cross may reach 100% in low wind speed conditions



Conclusions

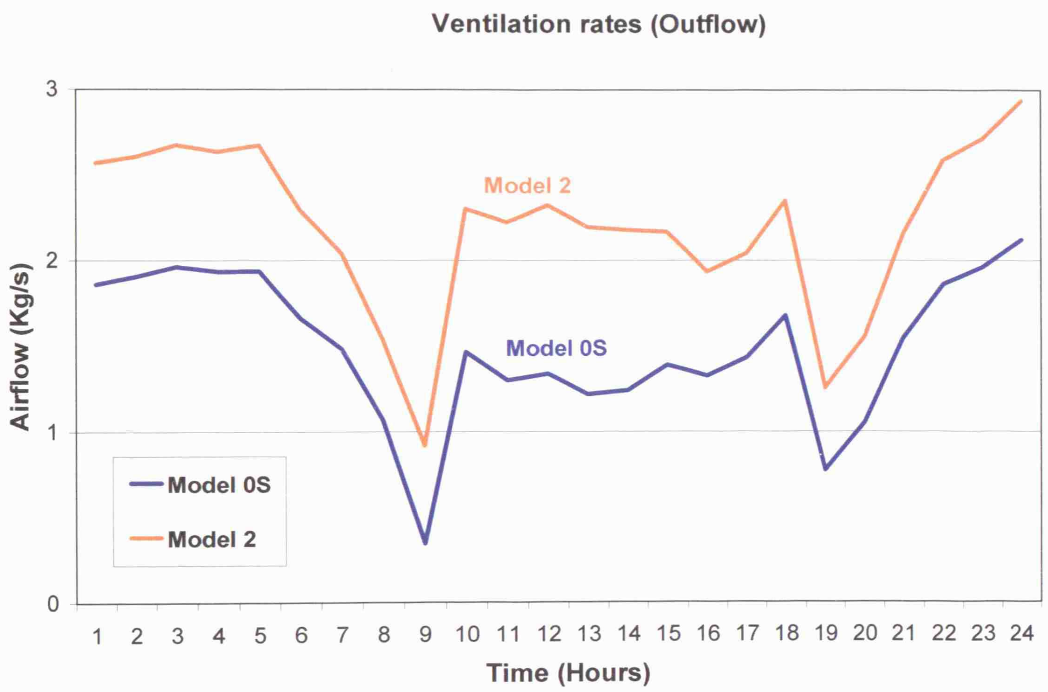
Introducing a solar chimney reduces slightly internal office temperatures while it may increase building solar gains. Total ventilation rates increase considerably. Stack driven air flow seems to reduce cross ventilation rates and most probably air flow patterns; this could have an effect on perceived thermal comfort.

7.1.2 Performance on a hot, still day

Investigation 2	
Simulation models	**Description / Features**
Model 0S	Model 0, sheltered
Model 2	Model 1, sheltered

Simulation Results

- Average daytime temperatures are reduced in Model 2 up to 1 C°
- Night time temperature differences between models are greater
- Ventilation rates for both models are greater during the night
- Ventilation rates for Model 2 are greater than Model 0S



Conclusions

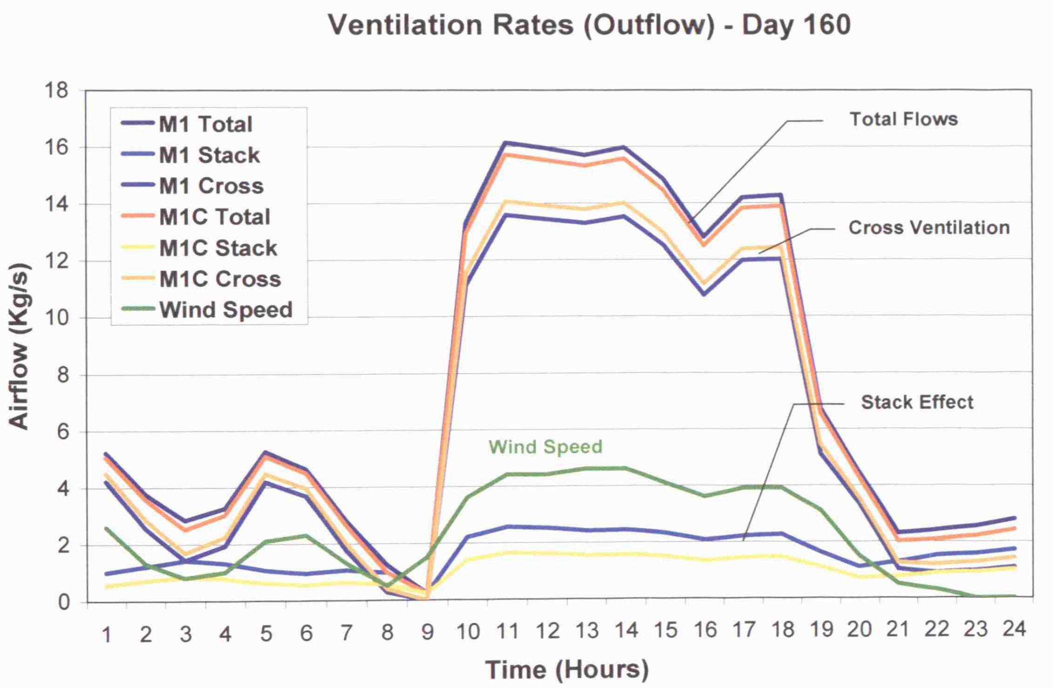
On a hot, still day a solar chimney may reduce average daytime temperatures by 1 C° and increase ventilation rates by 65%.

7.1.3 Reduced chimney width / solar exposure

Investigation 3	
Simulation models	Description / Features
Model 1	Basic Chimney model (4 m)
Model 1B	Model 1, 25% < width, chimney apertures
Model 1C	Model 1, 50% < width , chimney apertures

Simulation Results

- Small increase in average day time temperatures
- Significant reduction in total air flows
- ~50% Reduction in day time stack ventilation
- Very small reduction is solar gains

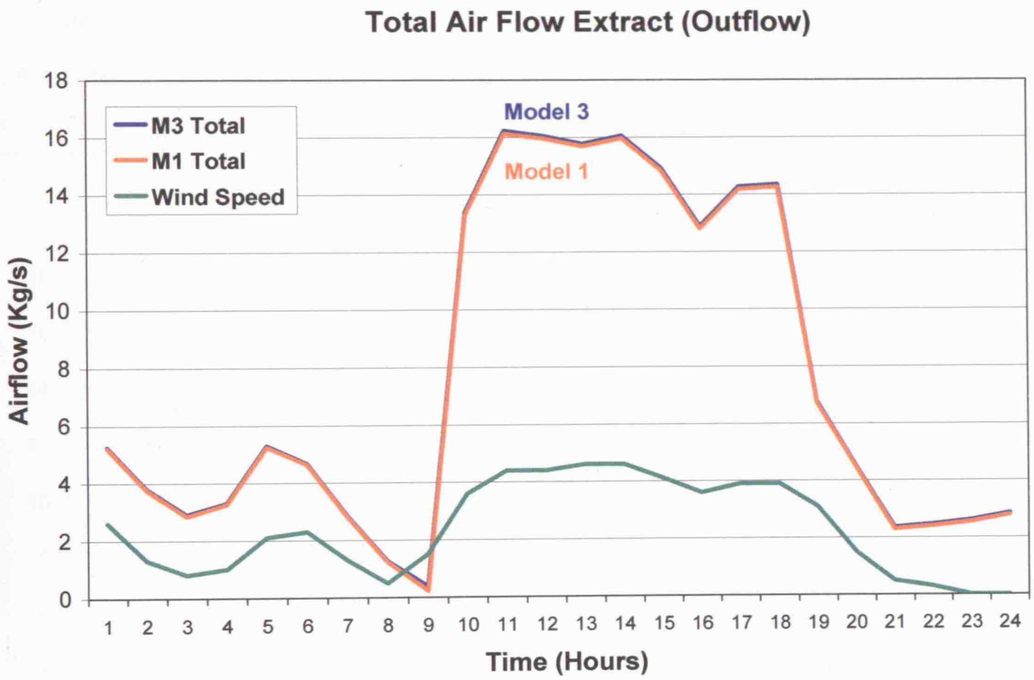


Conclusions

Reducing the width of the chimney while keeping the aperture area the same, results in slightly lower solar gains however, stack driven ventilation is considerably reduced (~60%). Overall ventilation reduction for Model 1C is ~3.5%. Consequently indoor temperatures are slightly increased.

7.1.4 Increased top chimney aperture

Investigation 4	
Simulation models	**Features/ Description**
Model 1	Basic solar chimney model
Model 3	Model 1, > 50% top chimney outlet
Simulation Results	
▪ Negligible temperature reduction ▪ Negligible air flow increase	



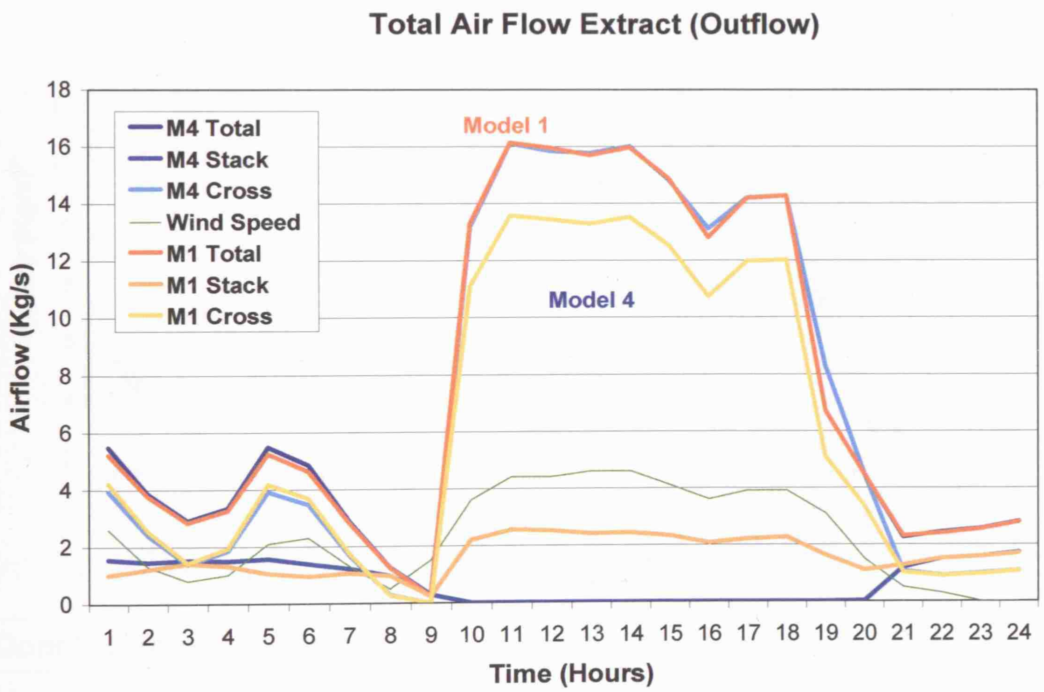
Conclusions
Increasing top chimney aperture and thus reducing air flow resistance at the chimney exhaust does not significantly affect building model air flow and temperatures.

7.1.6 Outlet orientation

Investigation 5	
Simulation models	**Description / Features**
Model 1	Basic solar chimney model (North)
Model 4	Model 1, south orientation (prevailing wind)

Simulation Results

- Small increase in average day temperatures
- Total ventilation rates do not vary significantly (in quantity)
- Stack ventilation eliminated during day time but increased during night time
- Considerable chimney back flows



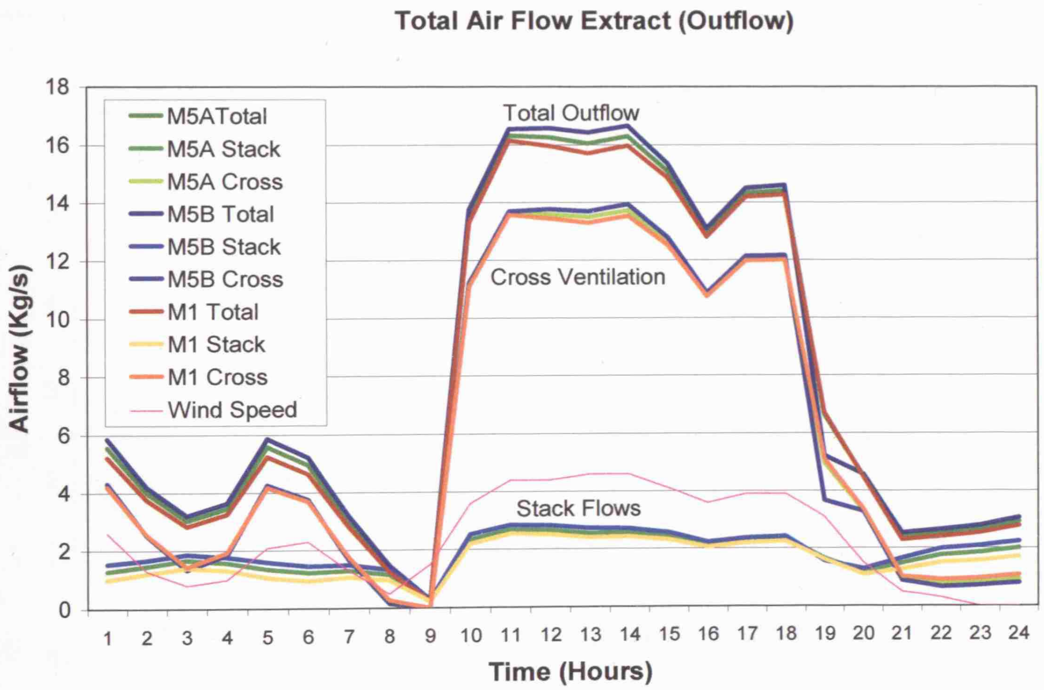
Conclusions

Locating the top chimney aperture (outlet) on the windward side of the building may seriously inhibit, even eliminate, stack flow. Substantial back flows in chimney cause rising warm air to escape through main office spaces resulting in higher temperatures. On the other hand night time stack ventilation may increase as winds shift direction.

7.1.6 Increased chimney height

Investigation 6	Increase chimney height, stack effect
Simulation models	**Description / Features**
Model 1	Basic solar chimney model, 6m above roof
Model 5A	Model 1> 50% chimney height (9m)
Model 5B	Model 1> 100% chimney height (12m)
Simulation Results	

- Small reduction in temperatures mostly during night time
- Increase in total air flow, cross ventilation and stack
- Per cent increase in stack flow is reduced for Model 1B

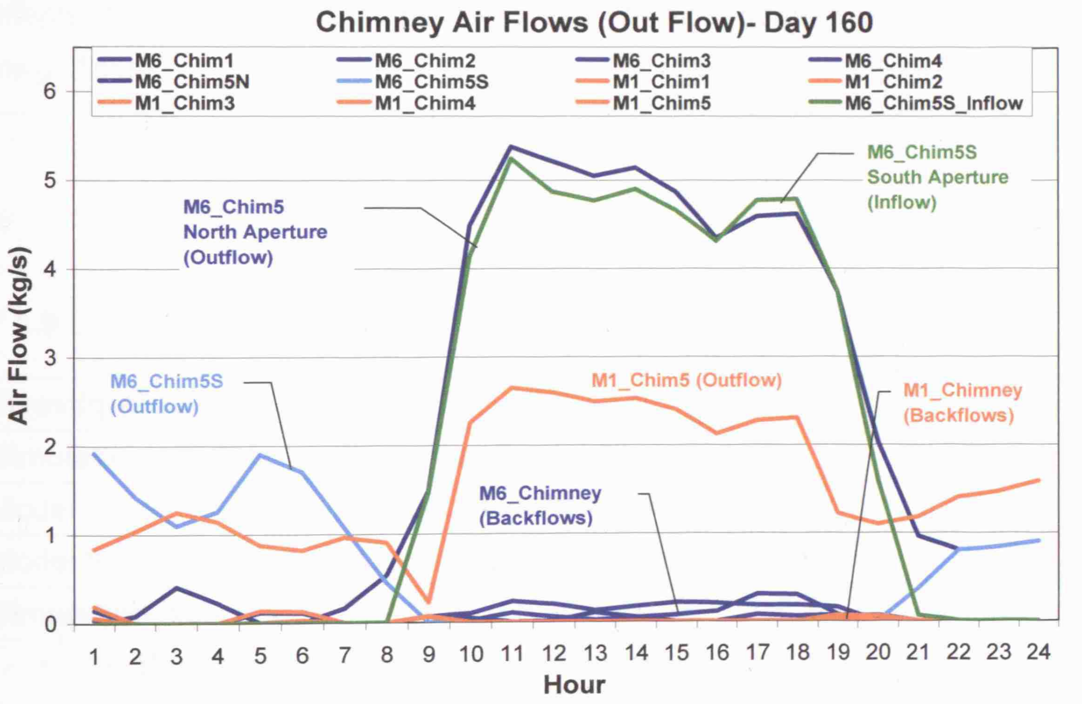


Conclusions
Increase in chimney height increases stack effect ventilation although the rate of increase is reduced with chimney height. Temperature reduction is negligible.

7.1.7 Double chimney outlets (North / South)

Investigation 7	
Simulation models	
Model 1	Basic solar chimney model (North)
Model 6	Model 1 + south aperture
Model 6S*	Model 6, sheltered (still day)
* Results for Model 6S are displayed in the overall model graphs for clarity	
Simulation Results	

- Small increase in average day time temperatures.
- Small reduction in night time top office floor temperature
- Ineffective air flow, back flow



Conclusions

Locating two outlet apertures on the leeward and windward sides of the chimney is ineffective ventilation strategy. Air flow through the windward side of the chimney mostly exits straight through the leeward outlet and may even create considerable back flows. Night time stack ventilation may increase considerably when wind speeds reduced and there is a change in direction; this allows only top floor to cool slightly.

7.1.9 Increased chimney insulation

Investigation 8	
Simulation models	Features / Desctiption
Model 1	Basic solar chimney model (50mm)
Model 7	Model , insulation: 200mm
Simulation Results	
▪ Negligible reduction in temperatures ▪ Insignificant increase in air flows	
Conclusions	
A very small reduction in indoor temperatures may probably be attributed to the effects of increased insulation / lower heat gains. Change in air flow rates is insignificant.	

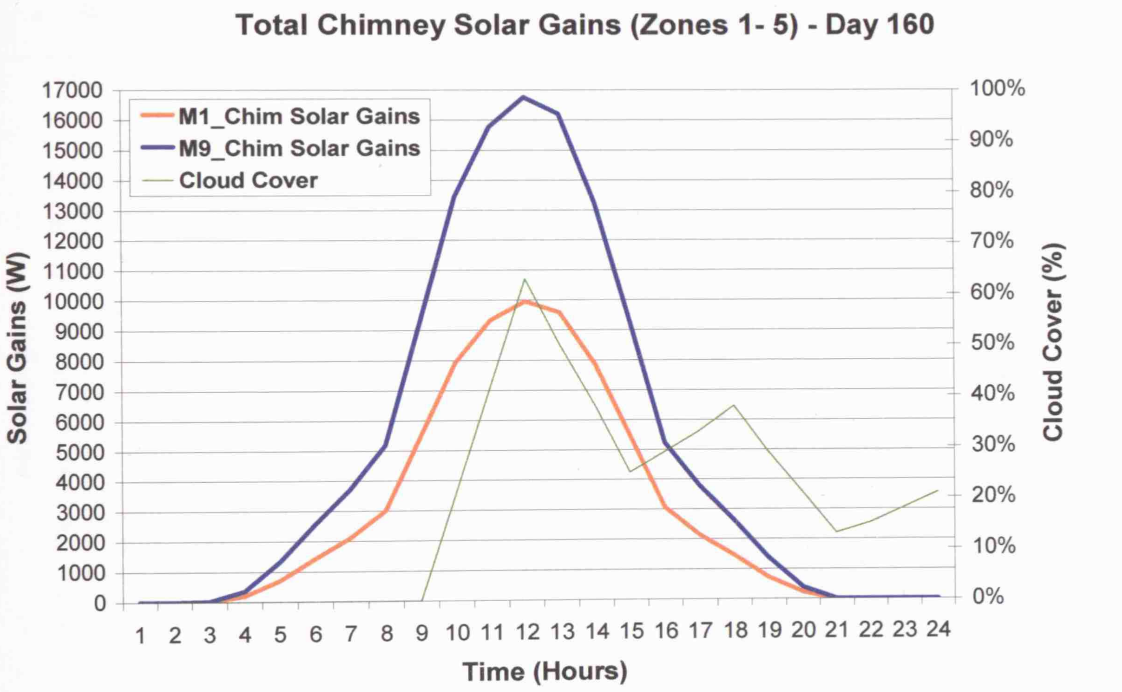
7.1.9 Sloped chimney top

Investigation 9	
Simulation models	Features / Description
Model 1	Basic solar chimney model, flat top
Model 8	Model 1, sloped top, aperture location
Simulation Results	
▪ No significant change in office temperatures ▪ Insignificant increase in air flows	
Conclusions	
A very small increase in air flows temperatures is probably possible by reducing air flow resistance at the top of the chimney shaft.	

7.1.10 Increased chimney absorptance

Investigation 10	
Simulation models	Features / Description
Model 1	Basic solar chimney model, (α:0,4)
Model 9	Model1 > absorptance (α:0,9)
Simulation Results	

- Insignificant rise in indoor temperatures
- Insignificant improvement in ventilation
- Considerable increase in chimney solar gains



Conclusions

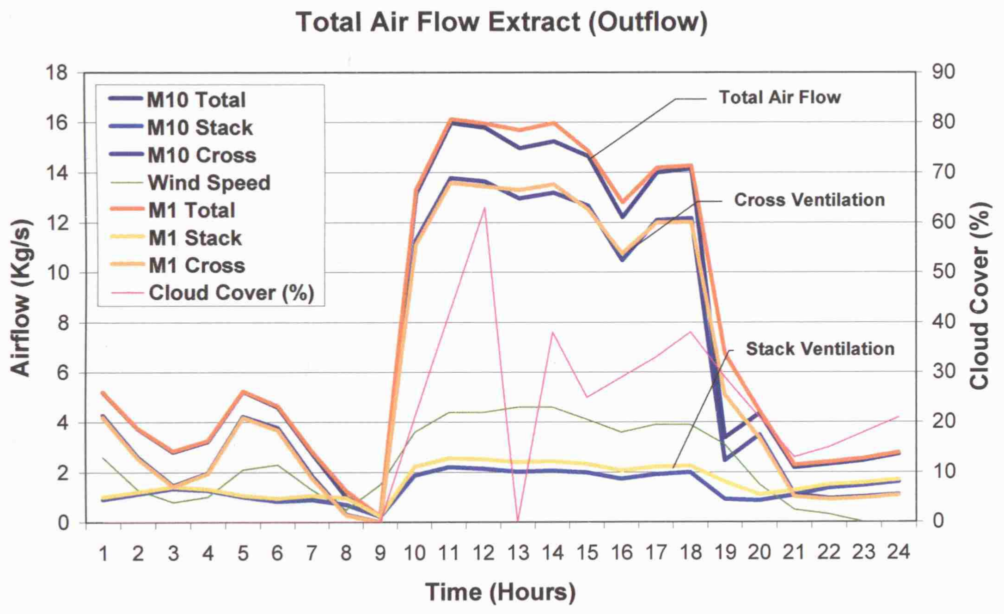
The solar chimney in Model 1 had already a fairly optimized thermal mass. Increasing the absorptance of the chimney wall although increased considerably solar gains did not effectively improve stack effect. Solar gains resulted in slight increase in temperatures.

7.1.11 Chimney location

Investigation 11	
Simulation models	**Features / Description**
Model 1	Basic solar chimney model, (max sun)
Model 10	Model 1, only top part exposed to sun
Model 10B	Model 10 > 50% top chimney outlet

Simulation Results

- Insignificant reduction in temperatures
- Small reduction in total air flow
- Considerable reduction in daytime stack ventilation (~20%)
- Small reduction in night time stack flows (up to 5%)



Conclusions

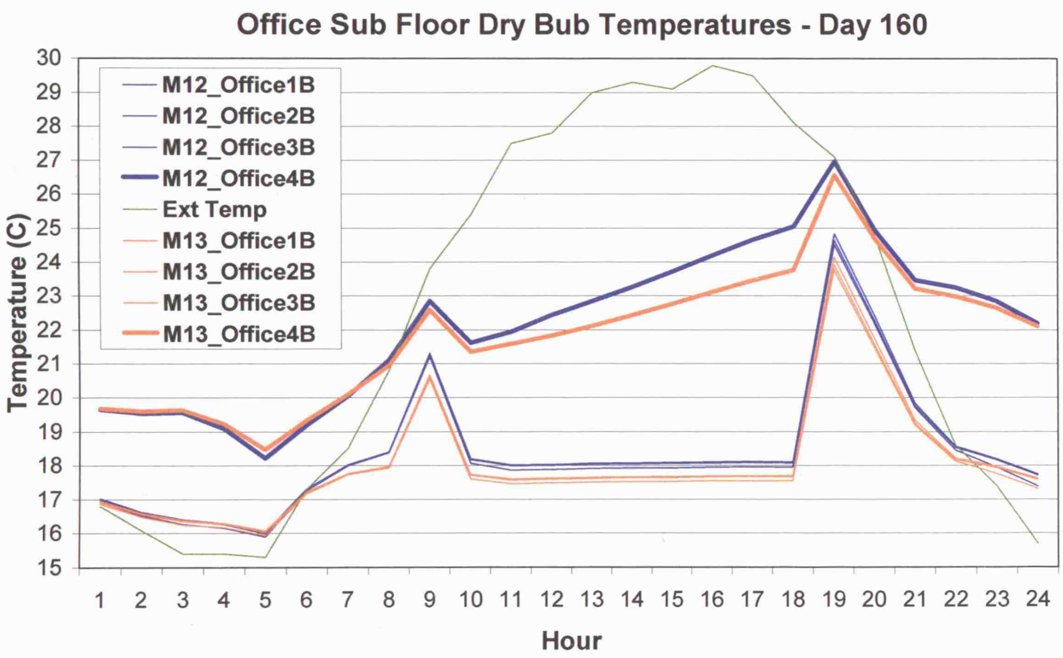
Locating the solar chimney in the center of the building model has two significant effects. It reduces solar exposure which is followed by a considerable reduction in stack flows (most notably daytime stack ventilation). On the other hand reduced solar gains result in slightly lower indoor temperatures. Night time stack flows are not greatly affected (max 5% reduction). Model 10B results are slightly improved regarding temperatures and air flows despite the increase in back flows noted mostly during late afternoon hours

7.1.12 Utilizing thermal mass

Investigation 12	
Simulation models	Features / Description
Model 0B	Model 0 + double concrete floors
Model 12	Mode 1, double concrete floor
Model 13	Model 12 > thermal mass (concrete fins)

Simulation Results

- Slight reduction in dry bulb temperatures
- Considerable increase in air flows (Model 0B / Model 12 comparison)
- Slight reduction in temperatures in Model 13 (Model 12 / Model 13 comparison)
- Considerable reduction in Model 13 sub floor temperatures when compared to Model 12 (despite similar air flow rates)



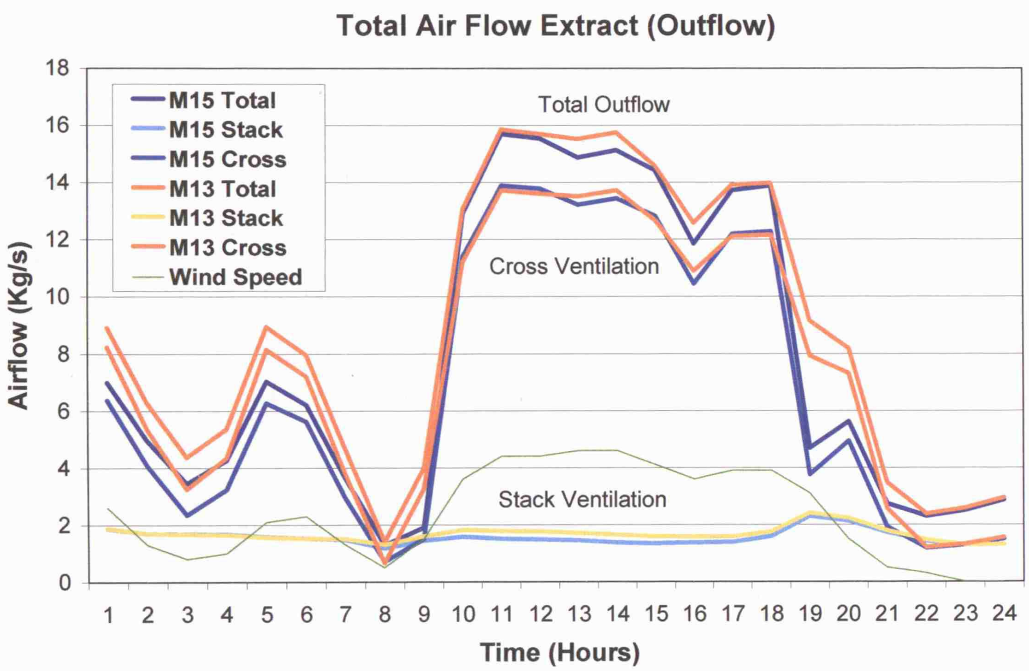
Conclusions

Utilizing thermal mass may help sustain cooler indoor temperatures. A solar chimney may help considerably drive air flow through constricted areas of buildings such as double / hollow floors thus improve convective heat transfers with thermal mass elements.

7.1.13 Combined solution: Chimney location and thermal mass

Investigation 13	
Simulation models	Features / Description
Mode 13	Best case thermal mass model
Model 15	Model 13 +Model 10 combined
Simulation Results	

- Slight reduction in temperatures in 2 upper floors; no change on first floor
- Slight temperature increase in ground floor
- Considerable reduction in total air flows (greater differences during night)
- Significant reduction in daytime stack flows, small during night



Conclusions

Increased thermal mass and cooling achieved in sub floor spaces in model 15 appears to reinforce night time stack effect and help sustain lower temperatures in upper levels. Daytime stack effect is considerably reduced for model 15 while cross ventilation rates are significantly reduced during night period.

7.2 Single day simulation: Overall comparison

Model performance is assessed and compared on several factors based on the available data from a single day simulation period (Appendix 3, p. 116). Compiled data relates only to the first floor space (Office 2 / Zone2) of each model. The environmental factors examined are:

- Average daytime dry bulb temperatures
- Average night time dry bulb temperatures
- Air flow types: total, stack and cross ventilation rates and
- Diurnal air flows: day and night ventilation

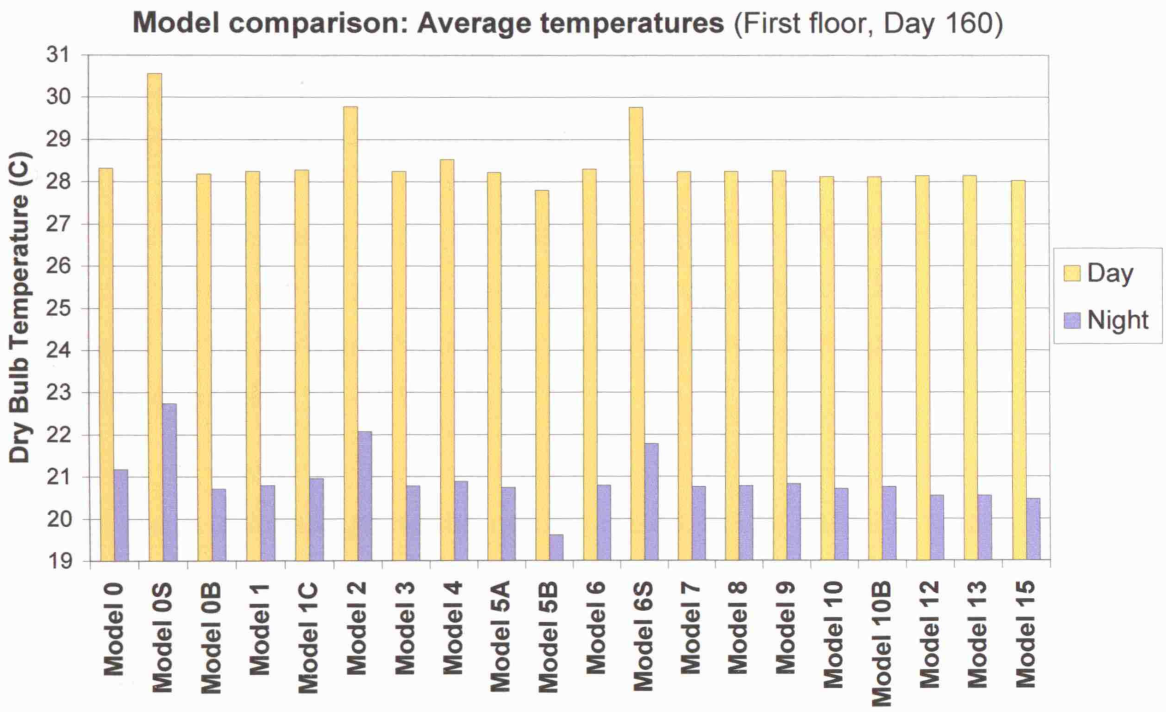


Figure 7.2.1 Model comparison of average dry bulb temperatures

A comparison on average day temperatures shows that a solar chimney may help reduce internal indoor temperatures although this reduction is usually negligible. On the other hand the prospects for night cooling seem slightly more encouraging. Maximizing chimney height (Model 5B) and utilising thermal mass in combination with a solar chimney (Models 12, 13 and 15) seem to bring about the best results.

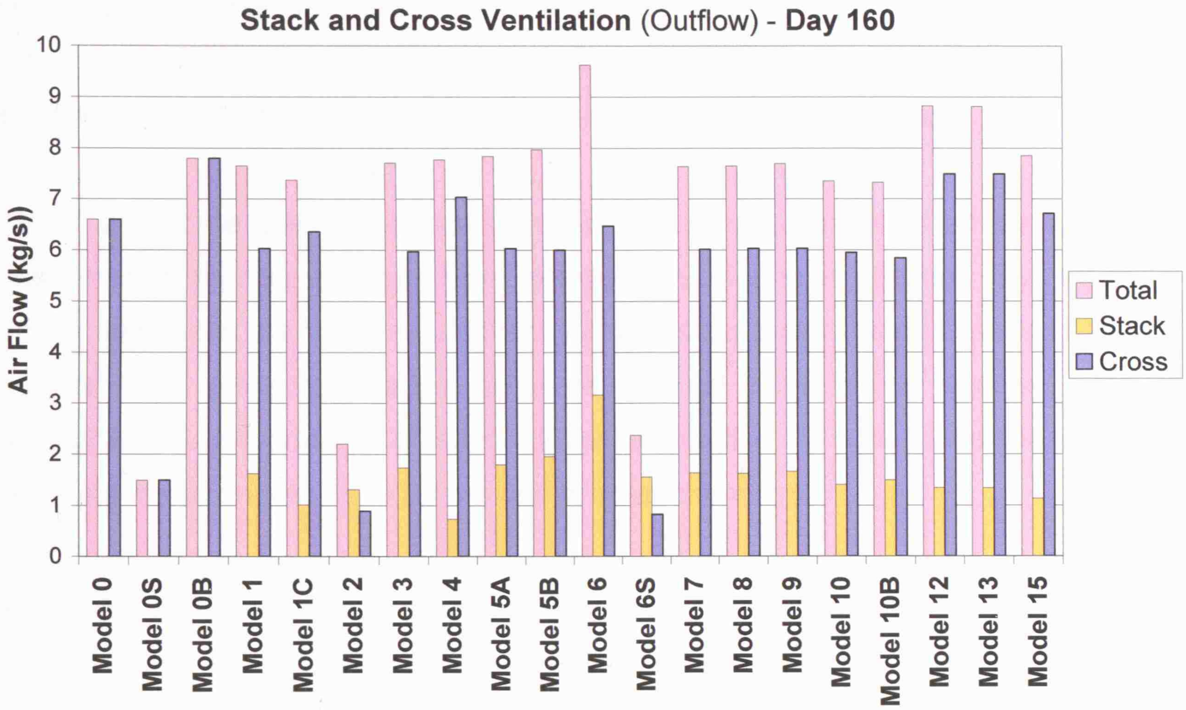


Figure 7.2.2 Model comparison of air flow types and performance

Figure 7.2.2 presents a comprehensive comparison of ventilation types. Additional graphs with model comparisons in groups, taking into account the considerable variation in amplitude of the different ventilation types, are included in Appendix 4, pages 117 -121.

The initial stage of investigating the models case by case certainly helps identify the quantity as well the actual quality of the ventilation rates achieved. For example, Model 6 seems to achieve great air flow rates yet we know that most of the air flow is not going though the entire building but only through the top two chimney apertures. Models 12, 13 and 15 perform well on total and cross ventilation rates but they have greater amount of apertures through the double floor vents. Actually it appears that total flows and cross ventilation rates in models with increased number of building apertures (Models 0B, 12, 13 and 15), stack driven ventilation is considerably reduced.

Solar chimney width, with the positive implications that this has to the chimney apertures, seems to play an important role in stack flow. Increasing chimney height has overall achieved higher rates in stack driven ventilation yet modifying chimney width seems to have a greater effect. Locating the solar chimney within the building model (Model 10, Model 10B) causes a considerable reduction in stack flow ventilation and a small reduction in cross ventilation rates.

There are some general remarks that can be made and verified by actual performance figures and graphical comparison. During a still hot day, stack driven ventilation via the actual chimney shaft, is equivalent and in many cases greater than cross ventilation achieved through main office spaces. This highlights the importance of stack driven ventilation in such conditions and presents the strongest case for the use of solar chimneys.

It appears that cross and stack ventilation are interrelated to such an extent that usually if there is an increase in stack ventilation it will create a reduction in cross ventilation and vice versa. This appears to be the case in the majority of the cases and is mostly dictated by existing wind forces and overall size and location of building apertures. However the effect does not mean that actual air flow is reduced through the main office windows. On the contrary, air flow and air speeds will probably increase with the use of a solar chimney.

From another perspective this phenomenon may have a significant effect in thermal comfort and the perception of cooling. On the one hand greater air flows and air flow speeds may enhance the cooling sensation yet they could also create discomfort due to draughts. The change in air flow patterns that will occur with the introduction of a solar chimney depends on location of main office windows and internal chimney apertures and will have an effect on thermal comfort. For example if fresh air enters through the windward side of the building and tends to flow upwards towards the internal chimney apertures and less across through the leeward side of the building, actual convective heat losses or simply the cooling sensation of occupants may be reduced.

A comprehensive comparison of diurnal ventilation rates is presented in figure 7.2.3. Additional graphs can be found in Appendix 4, pages 117-121. Diurnal rates which include stack and cross ventilation rates are mainly dictated by overall building aperture size and location. Solar chimney width (Model 1, Model

1C) followed by chimney height (Model 5A) are the most significant factors. Locating the top chimney aperture on the leeward side of the building is also extremely important.

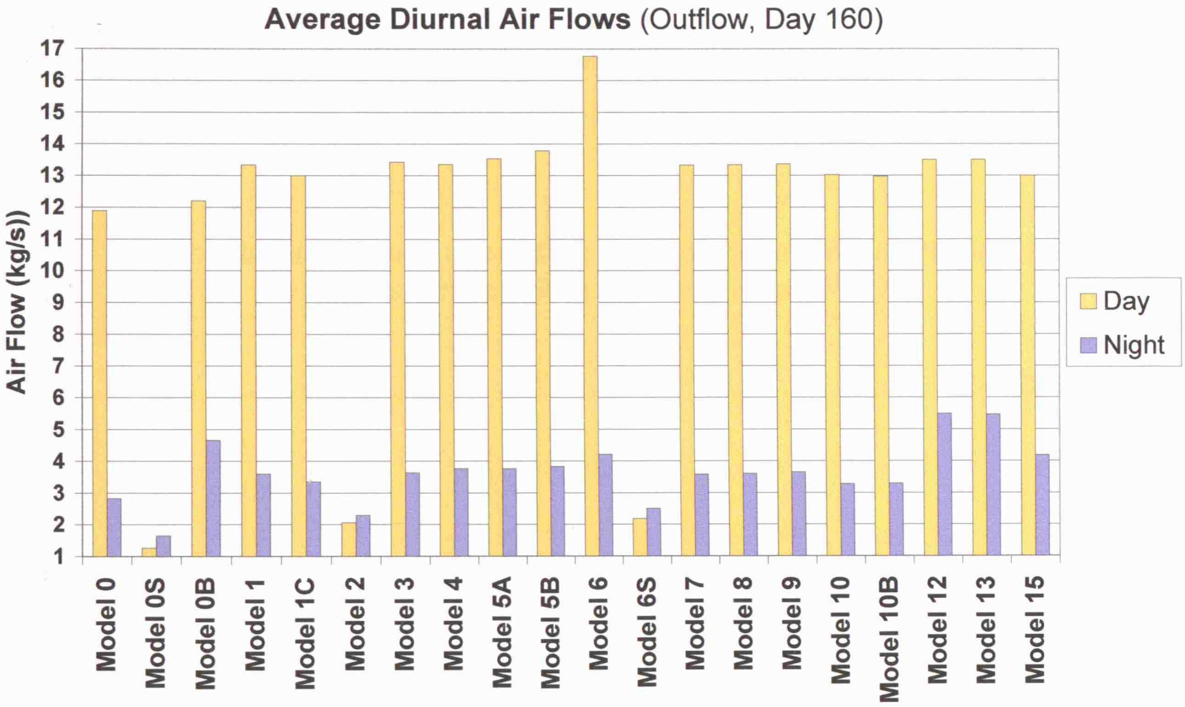


Figure 7.2.3 Model comparison in diurnal air flow rates

7.3 Model Comparison: Cooling Season (Days 120-270)

Simulating model performance over a longer period of time takes into account a greater number of environmental conditions and therefore offers more accurate results. The simulation period included the entire cooling season typically within days 120 and 270. Data is considered only for the first floor space (Zone 2) of each model. The following environmental factors are used to compare models:

- Resultant Temperature and
- Types of air flow: Total, stack and cross ventilation rates

Models are compared according to the percentage of hours that resultant temperatures reach or exceed 25 C° and 28 C°. According to Best Practice Program recommendations a natural ventilated building should not exceed a dry resultant temperature of 28°C and 25% for more than 1% and 5% of the year respectively. The main aim of the computer models devised was not primarily to be within these guidelines but rather to create the optimum conditions for comparing various solar chimney design factors. Comparison of resultant temperatures allows a better assessment in relation to thermal mass and overall thermal comfort. In this simulation data analysis actual cross ventilation rates through the double floors of Models 12, 13 and 15 is not taken into account.

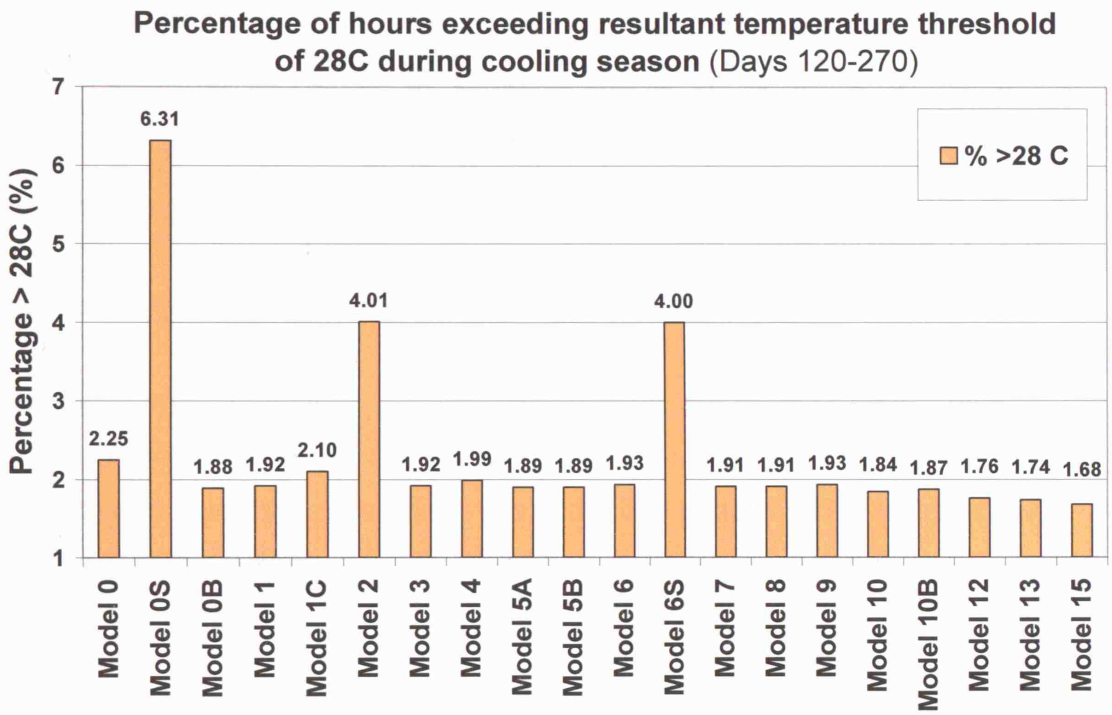


Figure 7.3.1 Per cent of hours exceeding resultant temperature of 28 C°

Simulation data in Figure 7.3.1 shows that on still days a solar chimney can help reduce by about 35% the occurrence of temperatures greater than 28 C°. On typical weather conditions the reduction is more likely to be about 15-16%. Increasing chimney width (Model 1 and 1C) and height (Models 5A and 5B) can help reach lower indoor temperatures.

Eliminating maximum solar gains by locating the chimney within the main building core (Model 10) is also significant. The most effective performance though is achieved by integrating thermal mass characteristics and solar chimney. (Models 12, 13 and 15)

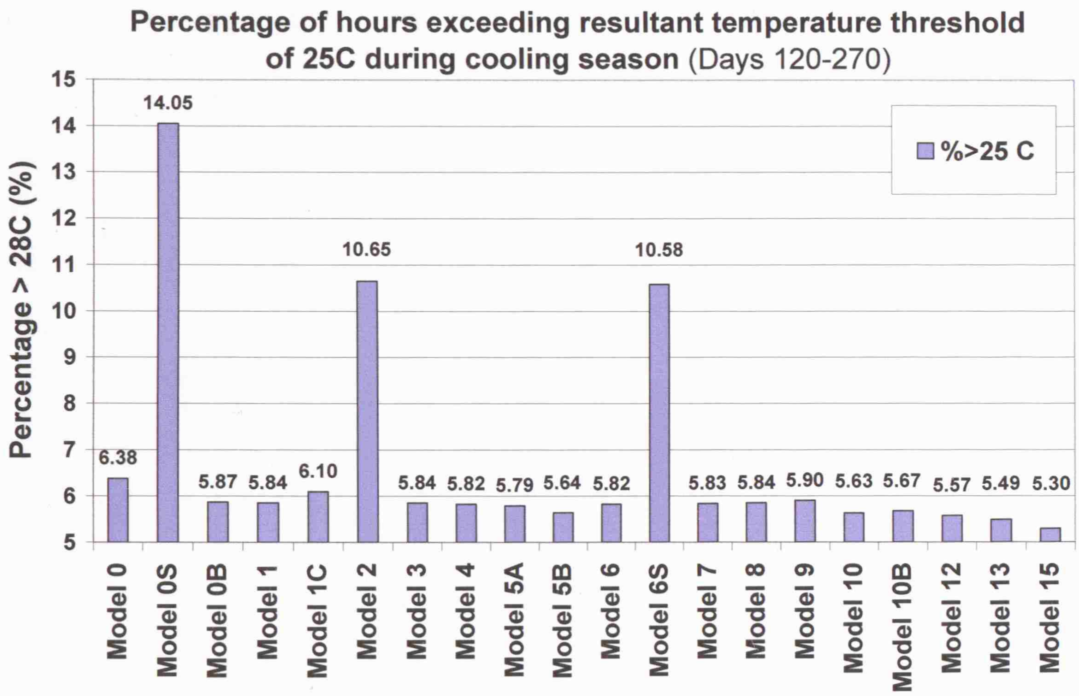


Figure 7.3.2 Per cent of hours exceeding resultant temperature of 25 C°

Simulation data in Figure 7.3.2 shows that on still days a solar chimney may reduce by about 24% the occurrence of resultant temperatures greater than 25 C°. On typical weather conditions the reduction is more likely to be about 12%. Chimney width, height, location and integrated use of thermal mass are again the most important factors.

Generally the results show that a solar chimney can help reduce indoor resultant temperatures during hot season. It is most effective in capping off peak temperatures (>28 C°) during still days (Models 2, 6S). Utilising a solar chimney for natural cooling can be almost as effective as enhancing thermal mass with the use of double floors. (Model1, Model0B)

Due to the considerable variation in amplitude of the different types of ventilation results are further examined in 2 groups:

- Group A: All models except group B
- Group B: Models simulated under no wind conditions: Model 0S, Model 2 and Model 6S (A comprehensive comparison of ventilation types for all models is presented in the Appendix 4 page 117-121)

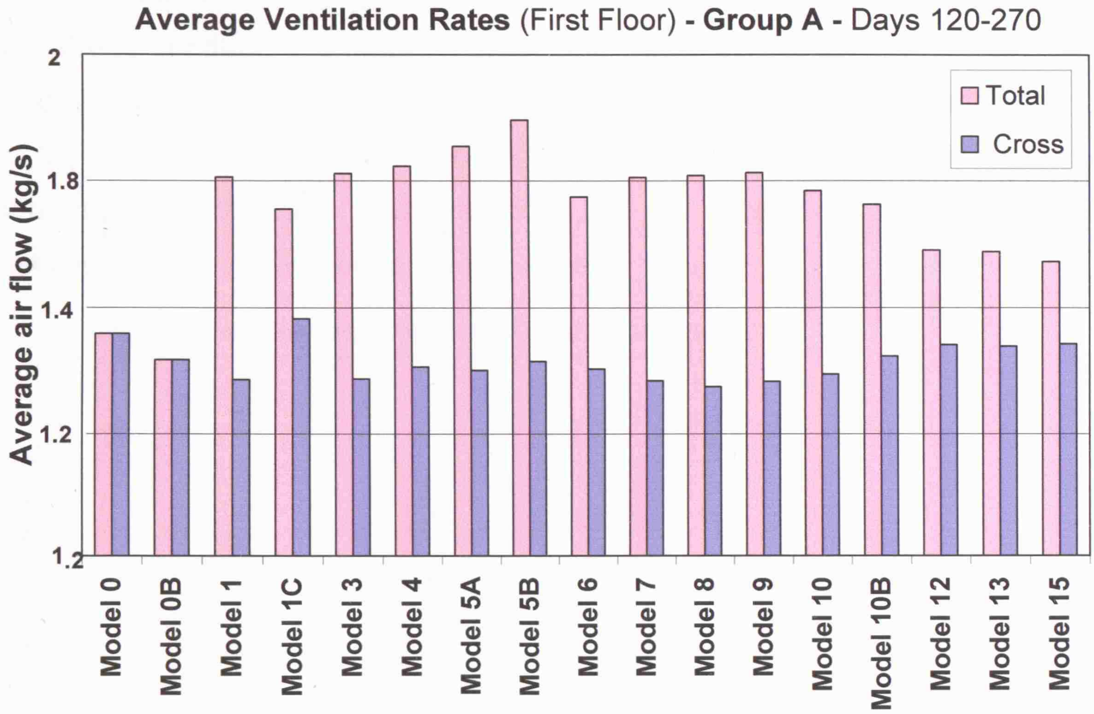


Figure 7.3.3 Total and cross ventilation rates fro Group A

Simulation data in Figure 7.3.3 shows that for the entire cooling season a solar chimney can increase the total ventilation rate by at least 22%. In still, windless conditions a solar chimney can enhance ventilation rates even further; at least up to 36%. (Figure 7.3.4)

comparison of stack ventilation rates (Figure 7.3.5) shows that increasing chimney height is probably the most effective method of augmenting stack driven ventilation yet chimney width can produce a more dramatic change. Reduction of chimney width by 100% (Model 1, Model 1C), a modification that also affects chimney aperture dimensions, resulted in a 56% loss of stack driven air flow. Reducing chimney height by 100% (Model 5B, Model 5A) resulted only in an 8% loss in stack flow.

Increasing the top chimney aperture may lead to a very small increase in flow if sufficient stack effect is taking place. In a situation where stack flows may be reduced (Model 10, Model 10B) then data shows that increasing the chimney outlet may lead to significant flow reduction (17%). Stack flows in models with a double floor system are considerably reduced (~52%). (Models 12, 13 and 15)

Overall these results again demonstrate the often reciprocal association of stack and cross ventilation. In many cases stack ventilation increase will lead to a reduction in cross ventilation, most notably in Models 1 Model 1C and Model 2. In Models 5A and 5B the opposite seems to be the case but this may be attributed to chimney downdraughts due to weather conditions; further investigation would be needed in this case.

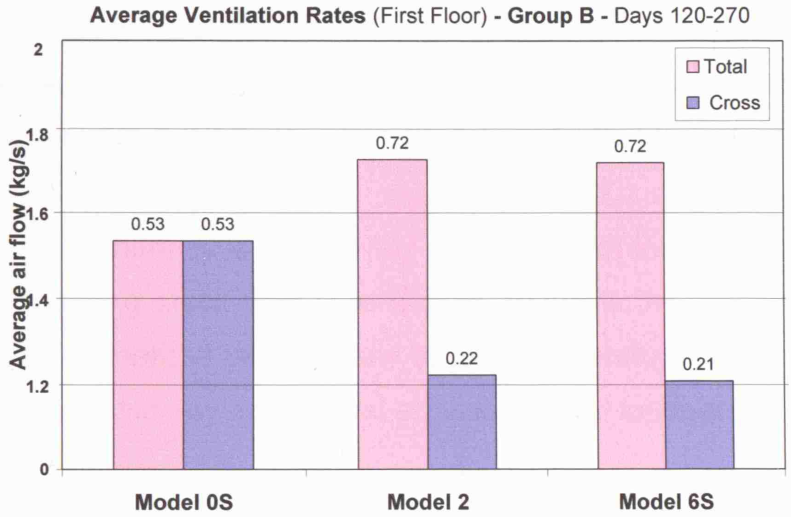


Figure 7.3.4 Total and cross ventilation rates fro Group B

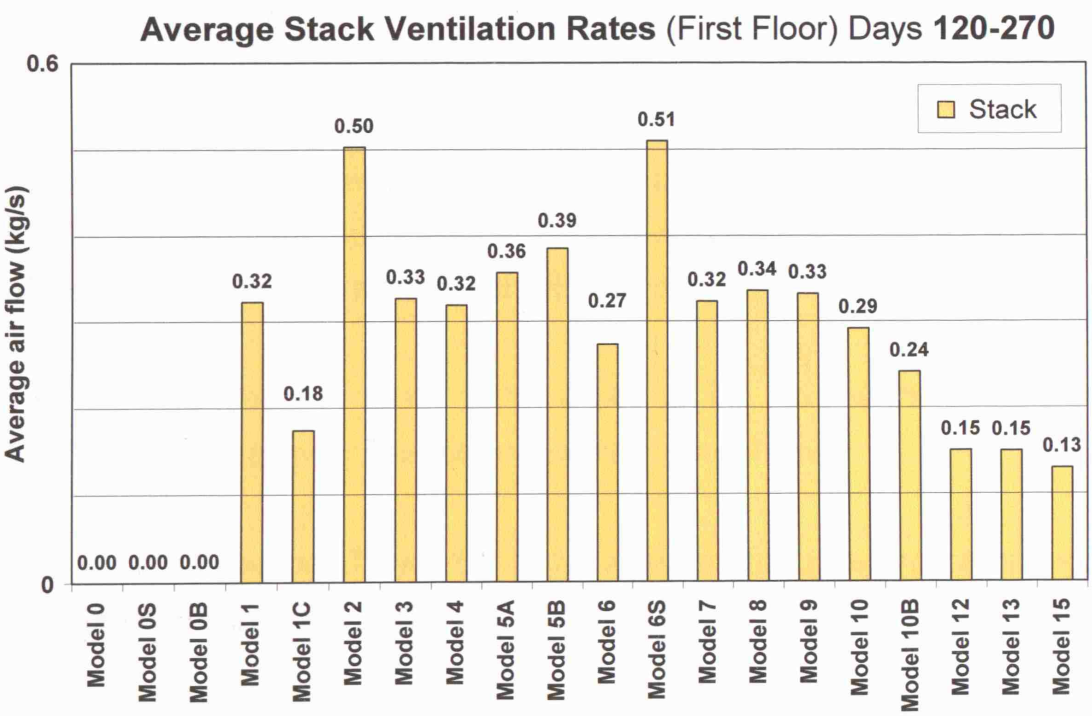


Figure 7.3.5 Stack ventilation rates for all models during cooling season

8. Conclusions

Buildings in the UK are associated with 40 to 50% of primary energy consumption thus improvement in building environmental performance becomes an increasingly important strategy in reducing energy use, pollution and global warming. Modern offices are energy demanding; their cooling needs during summer can be greater than heating during winter. Natural ventilation can offer significant benefits in human health and thermal comfort. A thorough understanding of ventilation types and methods is critical for the successful implementation of natural ventilation and passive cooling.

A solar chimney is a relatively novel concept for improving natural ventilation by introducing stack driven ventilation. Scientific research on the subject is limited and fragmented yet a review of existing literature helped reveal several aspects of solar chimney design and provided useful feedback.

Building simulation technology is an evolving tool that can offer a new platform for experimentation and improving environmental design. Understanding performance characteristics and implementation of solar chimney design in office buildings is pursued further with the aid of computer simulation. The computer software used is TAS Building Designer.

Based on literature review findings and initial assumptions 20 computer models (2 Basic Models + 18 Modifications) were used to examine 13 cases in solar chimney design. Building simulations were performed in two time periods:

- 24 hour period (Day 160); enabling the examination of model performance under specific environmental conditions.

- 5 month period (Days 120-270); allowing the assessment of model performance under greater variety of weather conditions.

The main environmental factors examined are:

- Dry Bulb Temperature (C°): Day and night time values

- Resultant Temperature (C°): Percentage above recommended thresholds
- Air Flows (kg/s): Total, stack and cross ventilation rates; Diurnal air flows

Simulation results were examined in each individual case and compared collectively.

In regards to passive cooling, simulations on 24 hour period showed that, a solar chimney may help reduce indoor temperatures yet these reductions may often be negligible. During hot, still days when wind driven cross ventilation is absent, the cooling potential of stack driven ventilation enhanced by a solar chimney becomes more significant. The possibility for cooling during the night period seems to be greater than day time.

Simulation data during the entire cooling season (150 Days) shows more encouraging results. On still days a solar chimney can help reduce the occurrence of resultant temperatures at or above 28 C° by about 35% (Model 0S, Model 2); on typical weather conditions the reduction is more likely to be about 15-16% (Model1, Model 5A). Integrating solar chimney use with optimum thermal mass resulted in a 25% reduction of the time exceeding the 28 C° threshold (Model 15). Solar chimney width, height and chimney aperture locations were the most crucial factors affecting performance. Minimising solar gain transfer into the main building, most notably locating the chimney within the building core (Model 10), can be quite effective.

Regarding the 25 C° temperature threshold simulations demonstrated that on still days a solar chimney may reduce by about 24% the number of hours exceeding the limit (Model 6S); on typical weather conditions the reduction is more likely to be about 12% (Model 10).

Simulation results showed that a solar chimney can create significant improvement in natural ventilation rates. Total ventilation rates may be increased by at least 22%. In still, windless conditions ventilation rates are enhance even further; at least up to 36%.

Stack ventilation introduced by a solar chimney can amount to about 20% of typical cross ventilation; during night time this may increase to at least 40-45% and on still days it may reach 100%.

Aperture size and locations are critical in controlling overall air flow rates. Solar chimney width and height seem to be the most important factors in increasing stack driven ventilation (Model 1, 1C, 5A, 5B). Stack effect is reduced when a chimney is used in conjunction with double floors yet it significantly improves the convective heat transfers occurring with the buildings thermal mass.

Stack and cross ventilation seem to be interrelated to such a degree that increasing the former may lead to a reduction in the latter, and vice versa. This may have a considerable effect in thermal comfort in terms of air flow speeds and flow patterns.

A solar chimney in general may help improve the quantity and quality of building ventilation rates yet the potential for passive cooling seems to be less promising. The limitations of the building simulation software (TAS) regarding the reduced temperatures of air introduced via a north orientation or shaded location, should be taken into account. Further research is needed to investigate more design options and individual parameters.

Solar chimney design depends on a number of natural factors as well as building characteristics therefore, it is quite complex. Building form and design can be controlled to a reasonable extent but the reliance on constantly changing, unpredictable weather conditions makes it imperative that specific design solutions are examined within a certain geographical location and microclimate.

Studies on a yearly basis and within a broader scope of work may reveal further design restrictions as well as possible uses such as, employing solar chimneys to augment passive heating.

Finally Table 8.1 presents some basic recommendations confirmed through the building simulation process; in conjunction with the findings through the literature review (Table 5.1, P. 41) these may provide some helpful guidance in solar chimney design and future research.

Table 8.1 Solar chimney design guidance

Parameter ***Change***	**Benefits + Drawbacks**	**Comments**
Solar chimney design elements		
Height *Increase*	Benefits	Improves stack effect and ventilation rates; good option for passive cooling
	Drawback	May have local building regulation restrictions
Width *Increase*	Benefits	Improves stack flow; allows optimized internal aperture size and location; may improve air flow distribution patterns
	Drawback	Increased solar gains in main building
Top chimney aperture *Increase*	Benefits	May increase slightly air flows in some cases
	Drawback	Vulnerable during night time, low stack pressures and wind
Thermal mass *Increase / Improve*	Benefits	Improves chimney solar gains, stack effect; helps with night time ventilation; may be used to control diurnal performance of chimney
	Drawback	May lead to greater solar gains in main building
Insulation *increase*	Benefits	Essential in minimizing solar gains in main building space
	Drawback	Minimal improvement in air flows
Inlet aperture *Location /size*	Benefits	Significant role in stack effect; important in air flow distribution paths; maximizing length reducing height and locating close to ceiling seem most effective strategy.
	Drawback	Shading necessary to reduce solar gains
2 Chimney outlets *Size/orientation*	Benefits	May enhance stack effect in certain conditions
	Drawback	May inhibit stack flow; create back flows
Chimney outlet *orientation*	Benefits	May act as wind-catcher.
	Drawback	Will inhibit even eliminate stack flow. Outlet should be located on leeward side of building.
Chimney location *exposure*	Benefits	Reduced heat gains in main building space
	Drawback	Reduced stack flow mostly during day time
Sloped chimney top *form*	Benefits	Slightly increases stack height; improves air flow
	Drawback	May expose outlet to winds/ turbulence and

		inhibit air flow. Best to keep outlet sheltered.
Absorptance *increase*	Benefits	Increase solar gains/ temperatures and may slightly improve air flow
	Drawback	Increases heat transfers in main building space
	Building design elements	
Building apertures *size, location*	Benefits	Combined with wind direction may enhance or restrict performance. enhance and control stack flow
	Drawback	May change NPL, inhibit stack flow. Must take into account occupant behavior and effect of aperture operation on stack flow.
Double floors *restricted areas*	Benefits	Stack induced ventilation may improve ventilation spaces restricted to external access and winds
	Drawback	Total stack flow may consequently be reduced
Thermal mass *improvement*	Benefits	Solar chimney enhanced ventilation in conjunction with improved thermal mass may lead to considerable reduction in temperatures; enhanced night cooling and cool storage.
	Drawback	Complicated design; construction and cost implications; air flow paths important
Air flows paths/patterns (stack vs. cross)	Benefits	Very important for effective convective heat transfers. May increase passive cooling, cooling sensation and comfort
	Drawback	May lead to discomfort; reduced cooling
	Weather and Microclimate	
Seasons *warm / cold*	Benefits	Warm, sunny weather improves solar gains and stack effect but also overall heat gains.
	Drawback	Cool temperatures may increase stack pressure differences and air flows but may also cause back flows in chimneys.
Wind *exposure*	Benefits	Wind may reinforce flow if air inlets are on windward side of building and outlet on leeward.
	Drawback	May inhibit stack ventilation, cause backflows
Urban *context*	Benefits	Solar chimney may help introduce air from advantageous location: north, cool/shaded areas of building, less polluted
	Drawback	UHI effect; over shading on solar chimney; building regulation restrictions

9. APPENDICES

APPENDIX 1

Simulation model Assumptions

Aperture size and air flow calculations

Using a 50% aperture opening in most simulation models the maximum *air mass flow rate* for any one aperture is typically no more than ~4kg/s

Density of air= m/v (mass/volume) = 1.12 kg/m^3

Thus max volumetric flow rate becomes= 4/1.12= 3.57 m^3/sec (per aperture)

Area of aperture (window pane) = 3.92m^2

So air speed of air through aperture= Volumetric flow rate/ Area of opening=

3.57/3.92= 0.91 m/s > than 0.8 max recommended value for comfort

(Best Practice Guide, CIBSE)

Thus wind speed is slightly above maximum recommended value.

Also a 50% aperture opening in most simulation models provides a maximum *ventilation rate* through the building of approximately 16.5 kg/s =

16.5/1.12= 14.7 m^3/sec

Recommended air flow for cooling 5-30 ACH (Best Practice Guide, CIBSE)

10ACH is= 10 x Total Building Air volume / Hour=

10 x (15mx15mx3m) x 4floors / 3600s= 7.5 m^3/sec

30 ACH cooling would be 22.5 m^3/sec

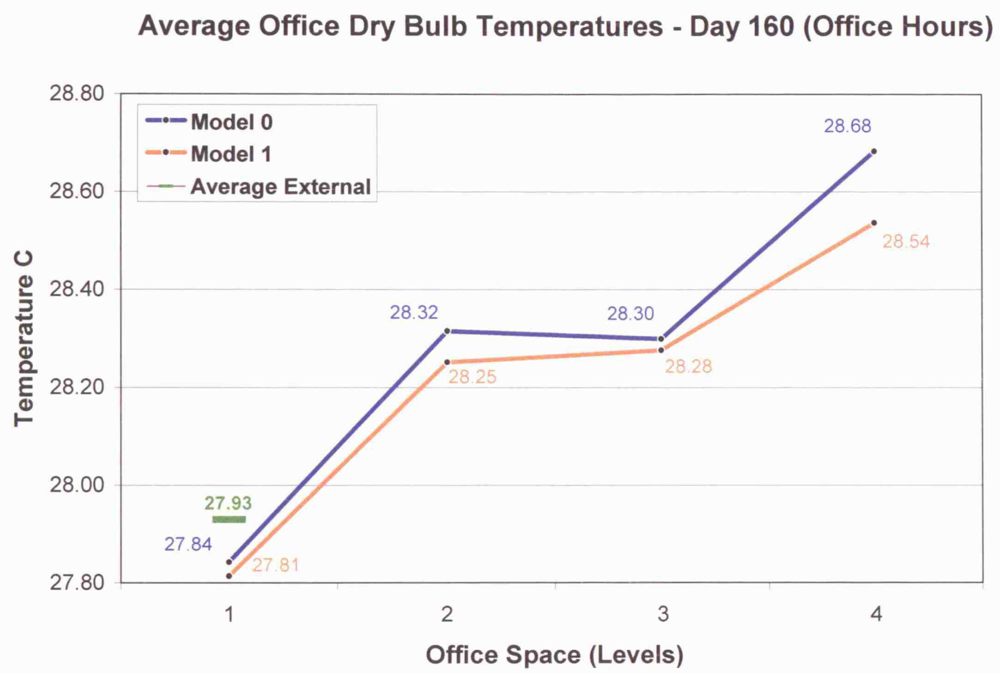
Therefore max air flow through building (reached during daytime ventilation) is well within recommended values.

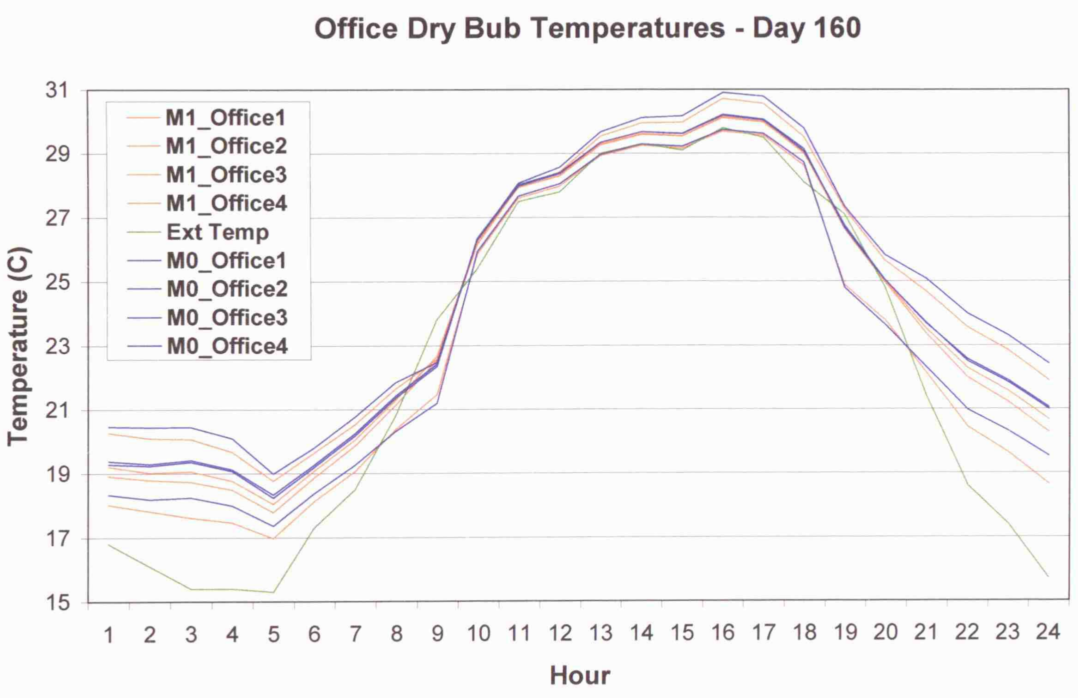
Based on these basic calculations a 50% aperture opening operation would be acceptable since the following be must taken into account:

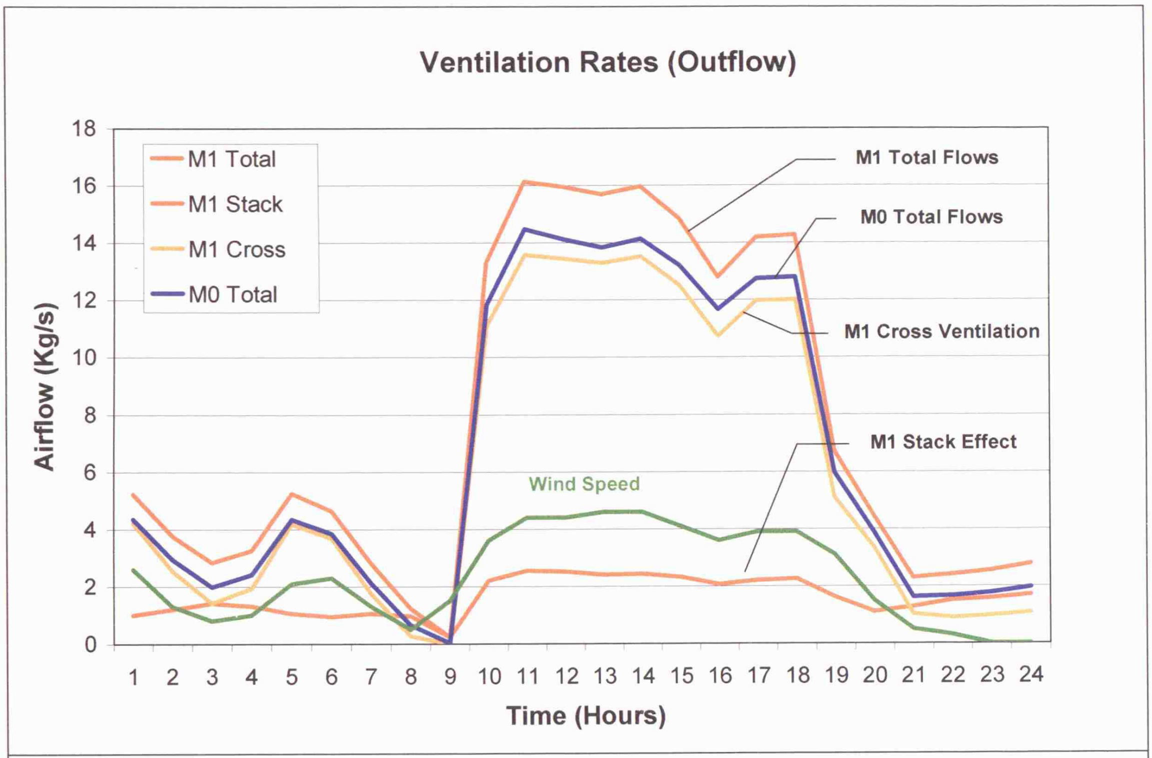
- Based on main assumptions simulation models have a reduced number of windows and effective window area for simplification purposes. In a more realistic environment incoming air flows would be spread out over wider window areas thus wind speeds would be reduced
- In worse case scenario screens/ wind buffers would limit direct air flow speed and discomfort.

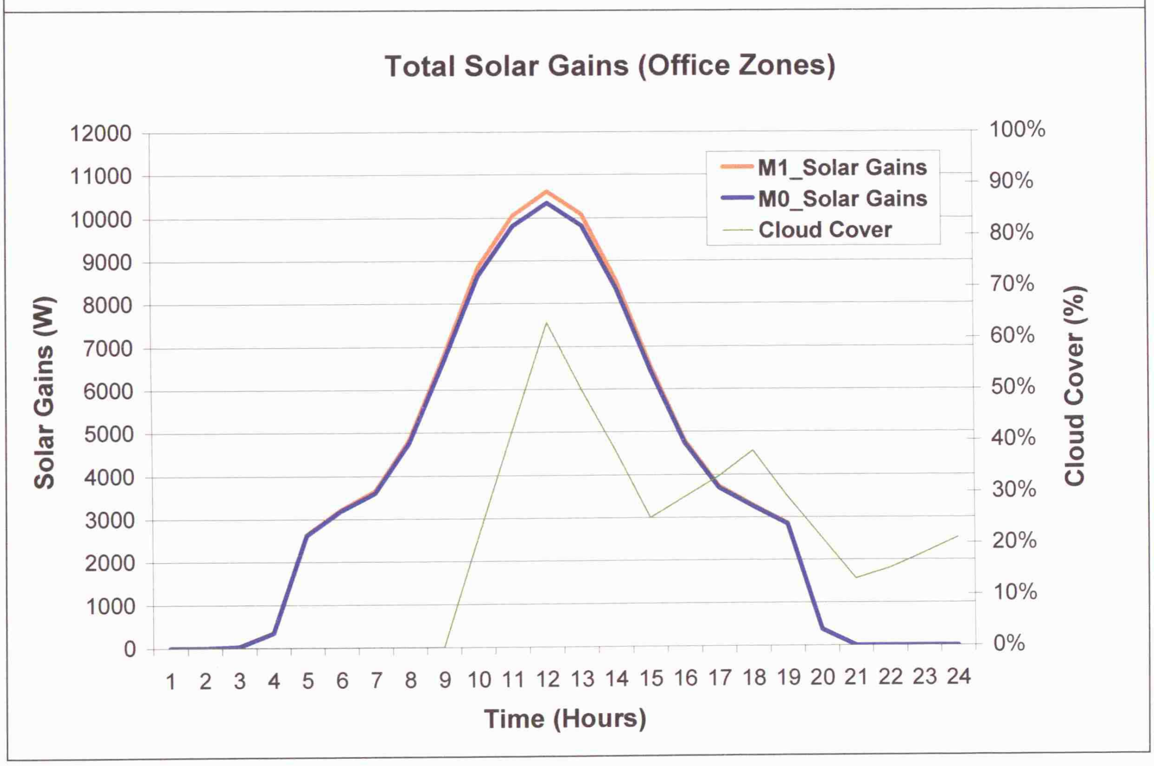
APPENDIX 2

Investigation 1	Introducing a solar chimney on the south facade
Simulation models	Description / Features
Model 0	Base case, cross ventilated office
Model 1	Model 0 + solar chimney (> stack effect)

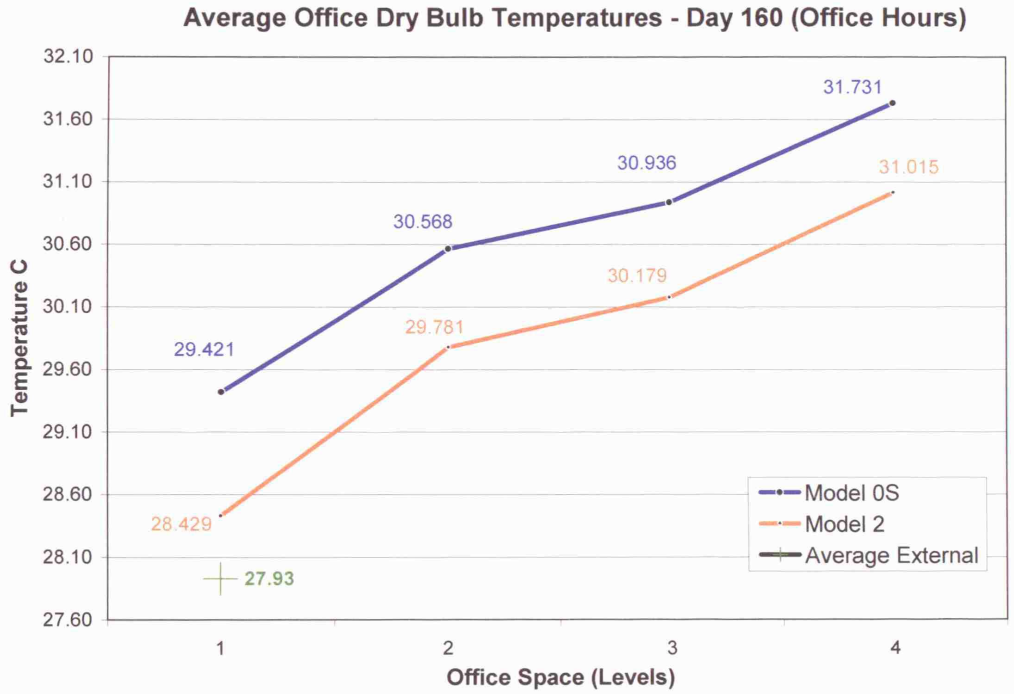


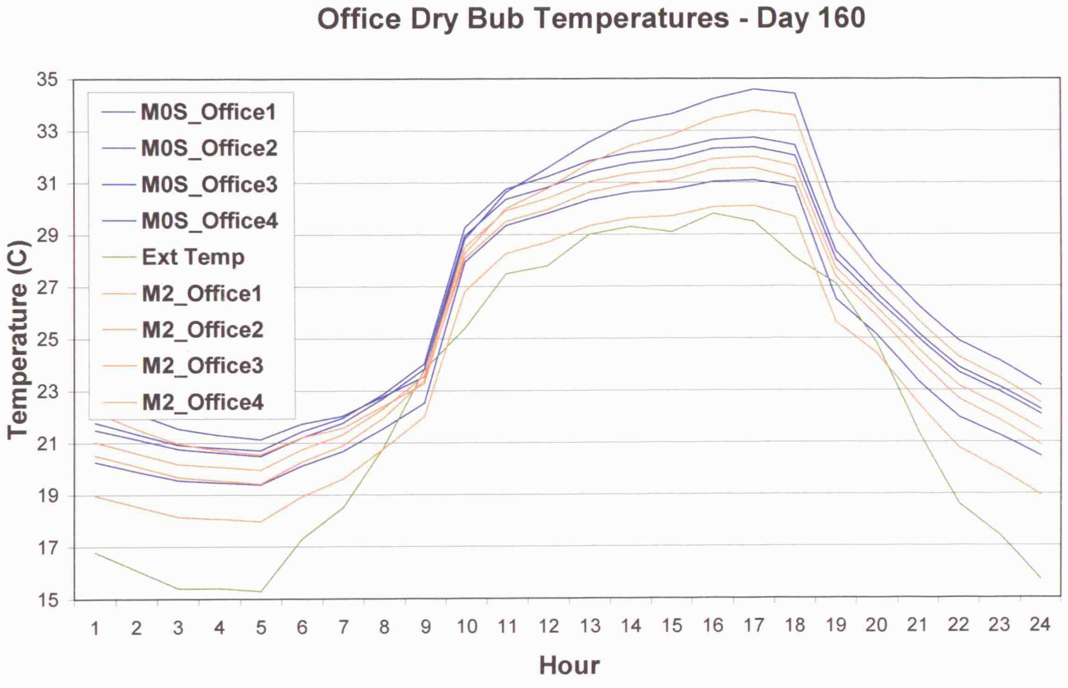


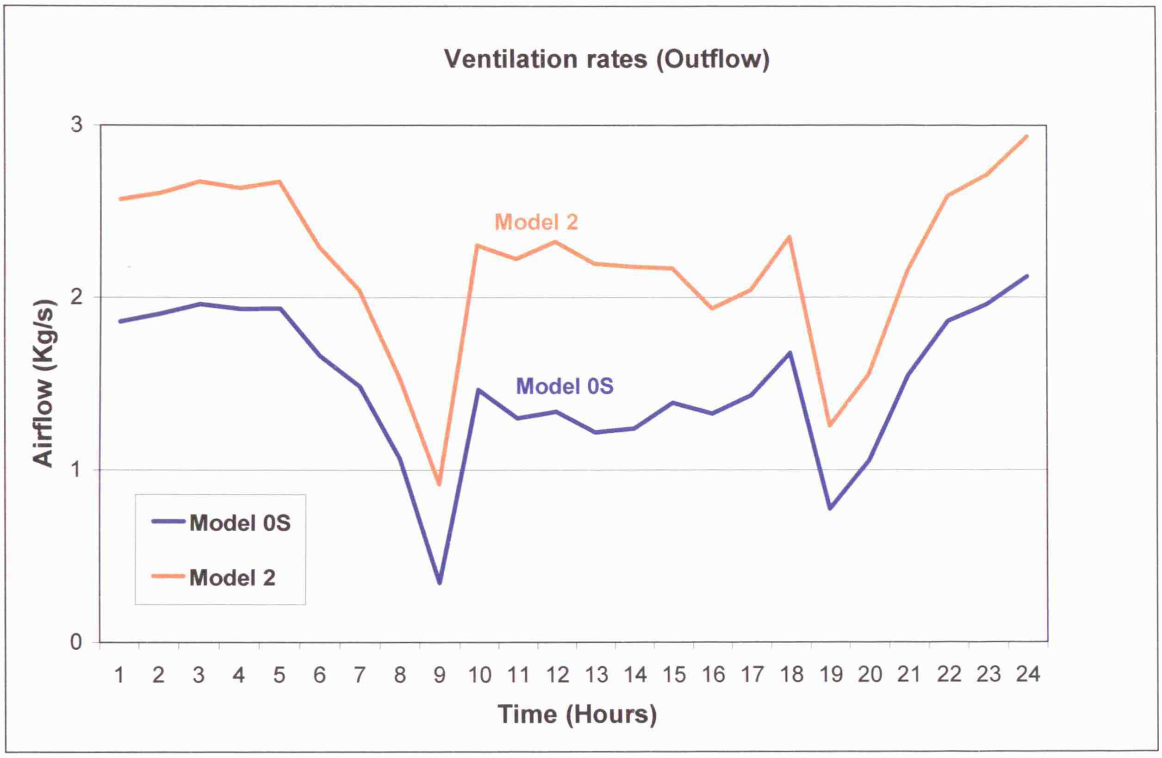

Ventilation Rates (Outflow)
Airflow (Kg/s)
Time (Hours)
M1 Total
M1 Stack
M1 Cross
M0 Total
M1 Total Flows
M0 Total Flows
M1 Cross Ventilation
M1 Stack Effect
Wind Speed


Total Solar Gains (Office Zones)
Solar Gains (W)
Cloud Cover (%)
Time (Hours)
M1_Solar Gains
M0_Solar Gains
Cloud Cover

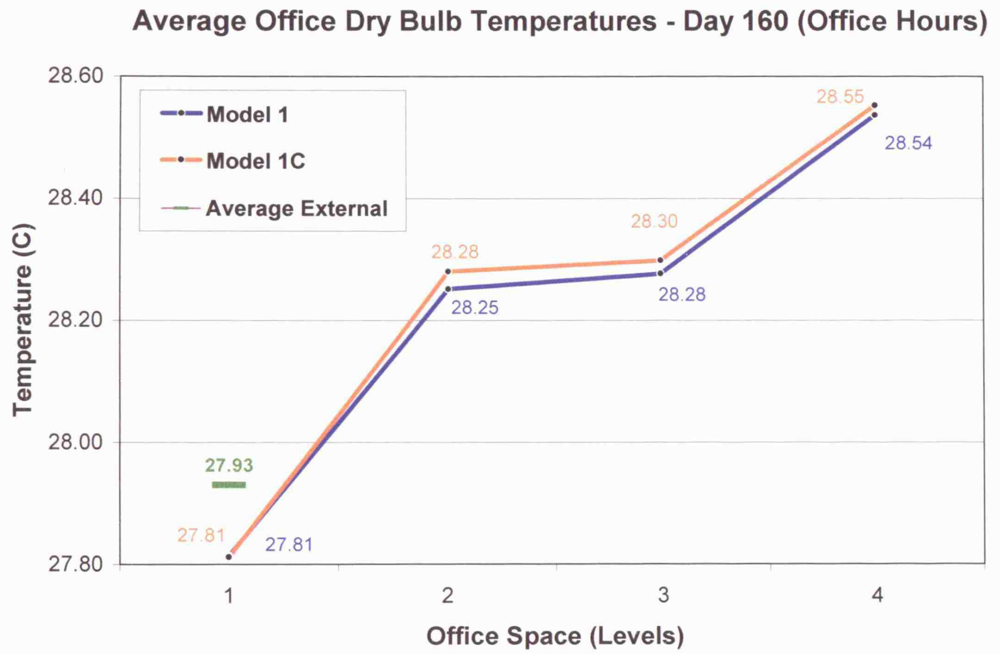
Investigation 2	Performance on a still day (no wind)
Simulation models	**Description / Features**
Model 0S	Model 0, sheltered
Model 2	Model 1, sheltered
Simulation Results	

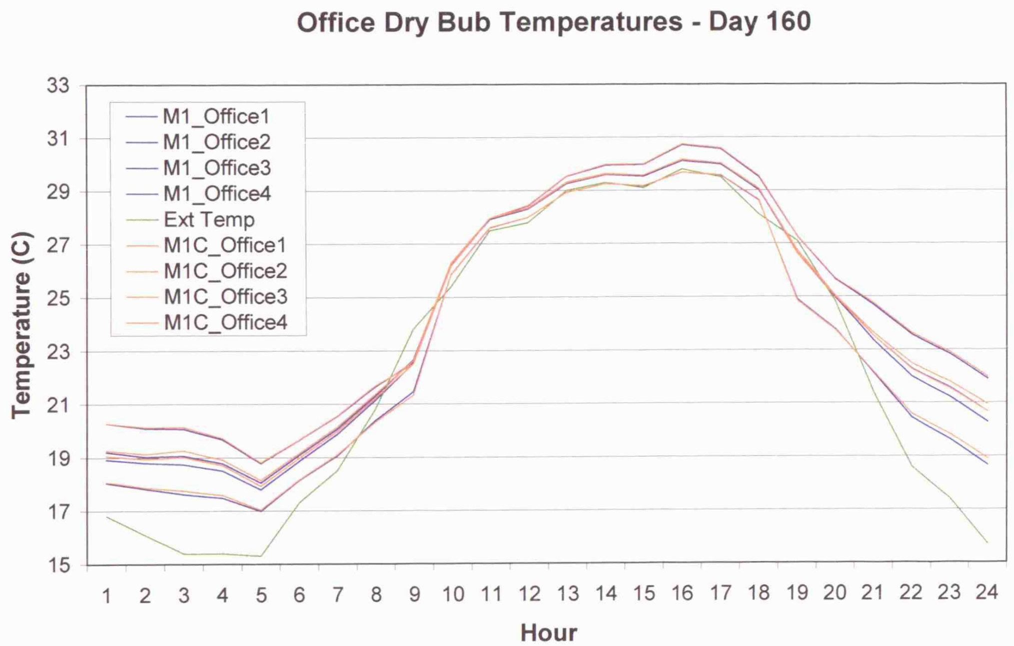


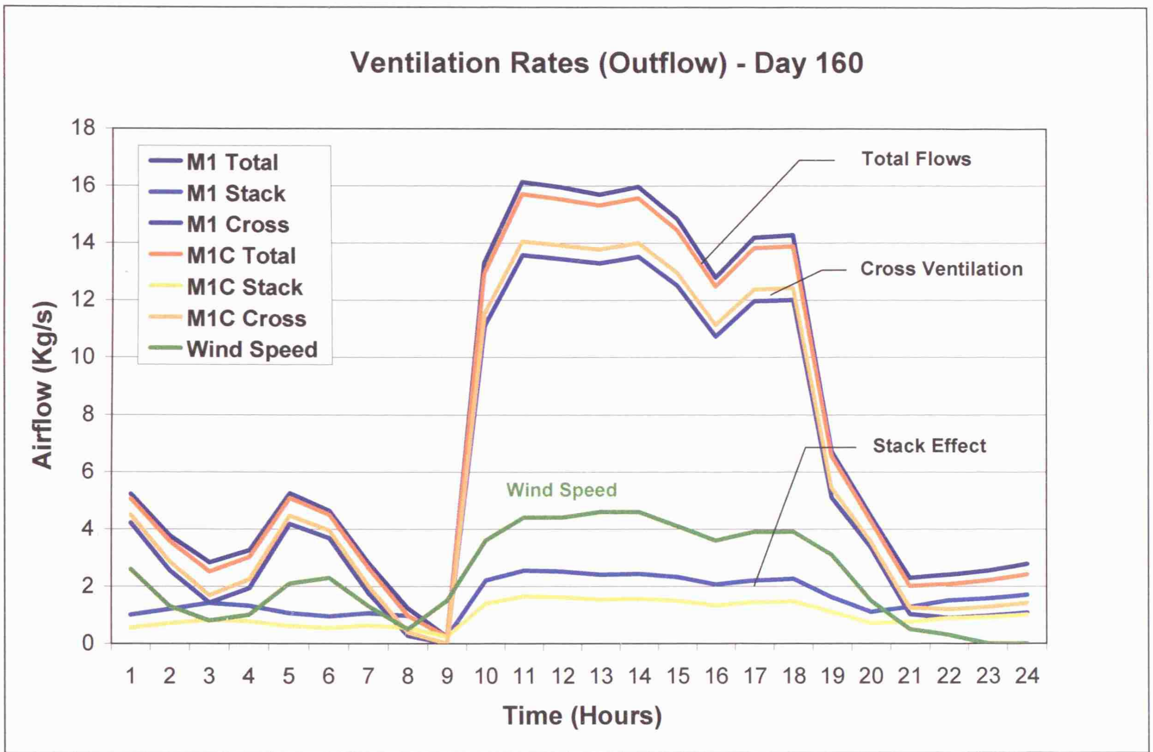


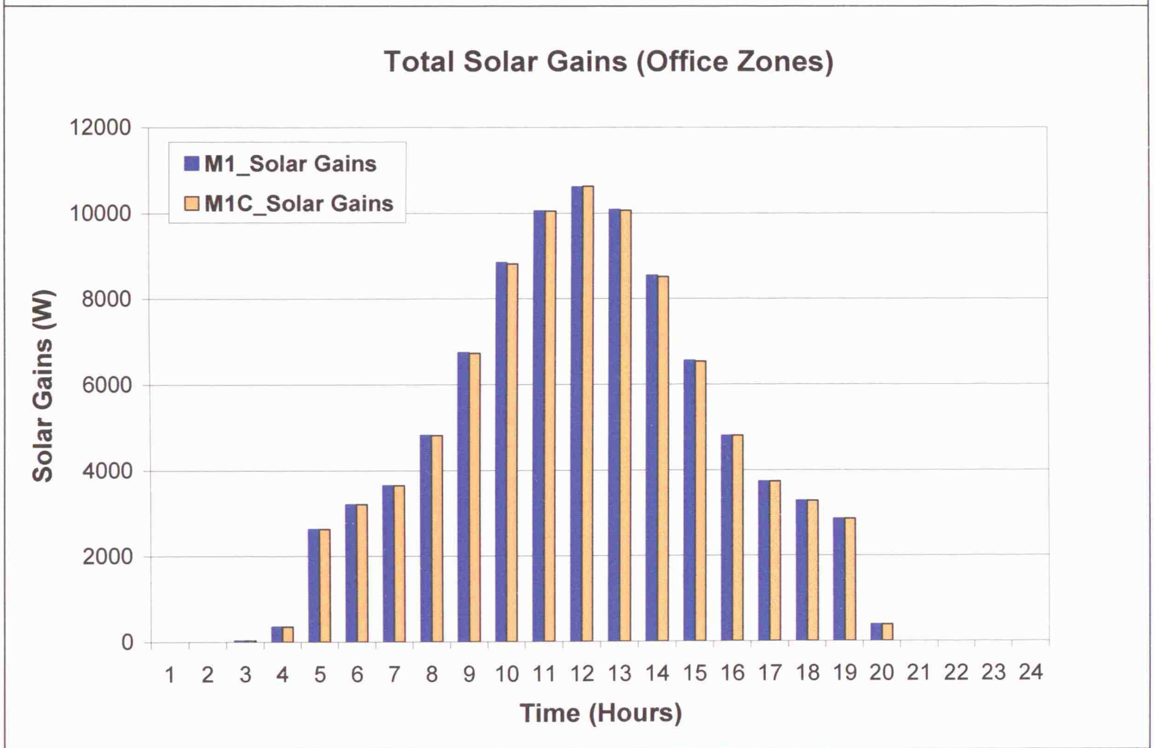

Ventilation rates (Outflow)
3
2
1
0
Airflow (Kg/s)
Model 2
Model 0S
Model 0S
Model 2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (Hours)

Investigation 3	Reduce width, solar exposure
Simulation models	Description / Features
Model 1	Basic Chimney model (4 m)
Model 1B	Model 1, 25% < width, chimney apertures
Model 1C	Model 1, 50% < width , chimney apertures
Simulation results	

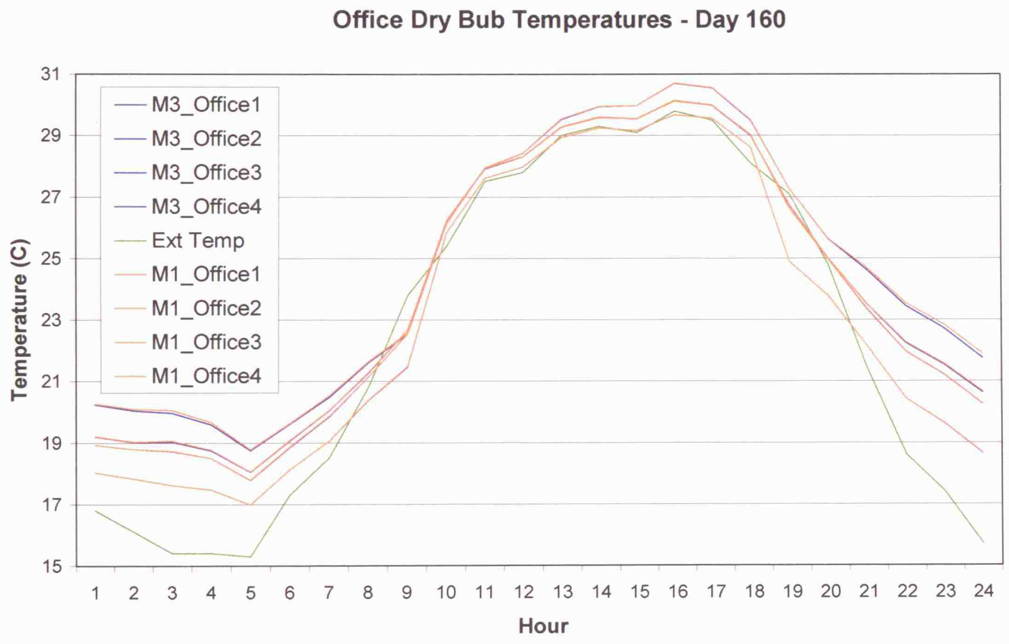


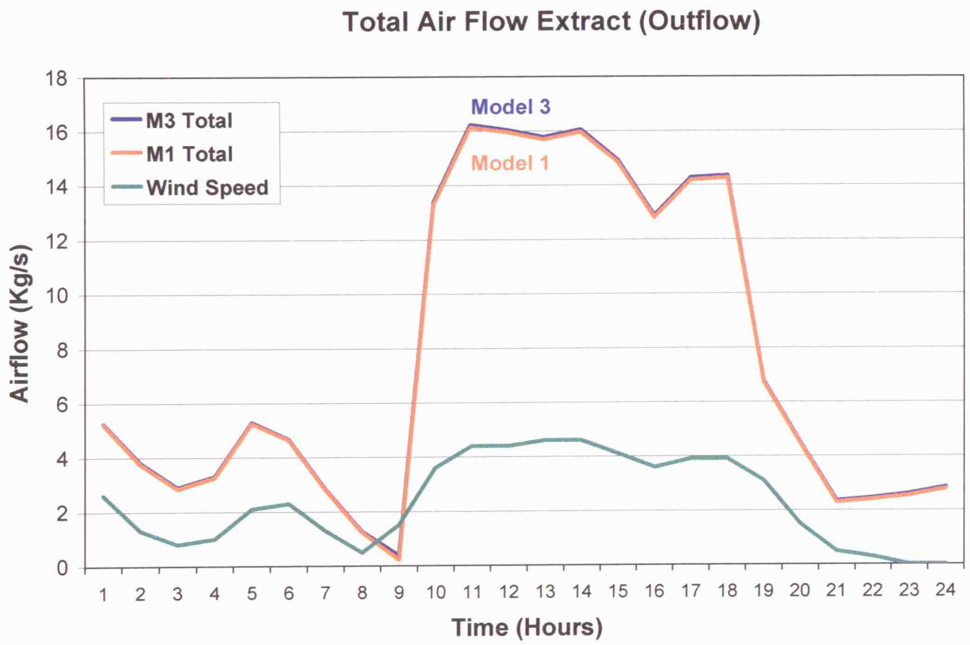



Ventilation Rates (Outflow) - Day 160
Airflow (Kg/s)
Time (Hours)
M1 Total
M1 Stack
M1 Cross
M1C Total
M1C Stack
M1C Cross
Wind Speed
Total Flows
Cross Ventilation
Stack Effect
Wind Speed
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

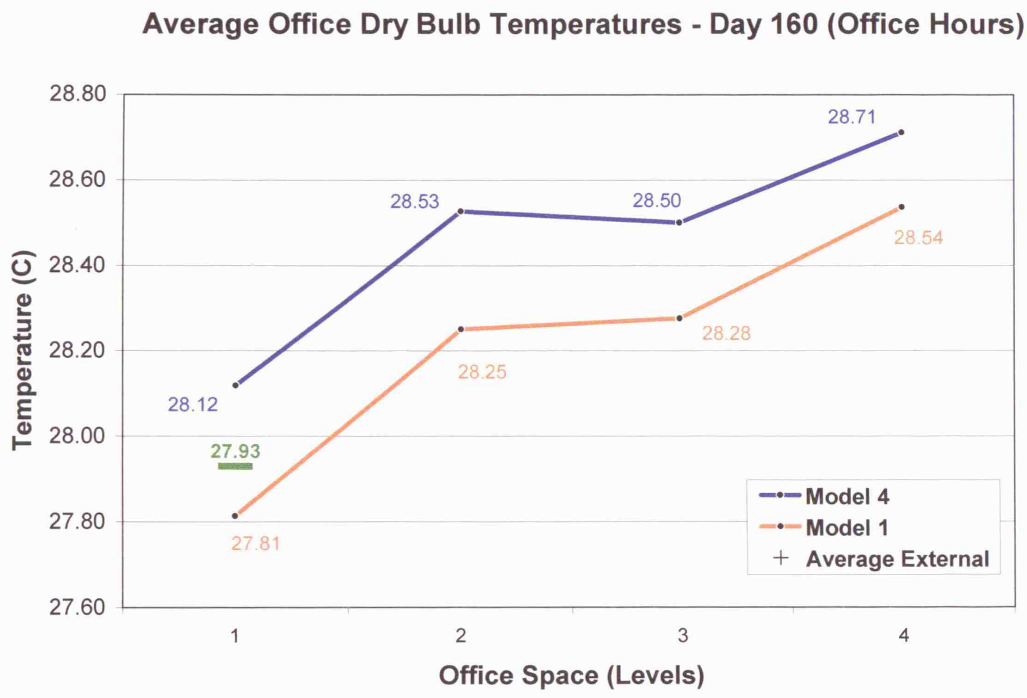

Total Solar Gains (Office Zones)
Solar Gains (W)
Time (Hours)
M1_Solar Gains
M1C_Solar Gains
0
2000
4000
6000
8000
10000
12000
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

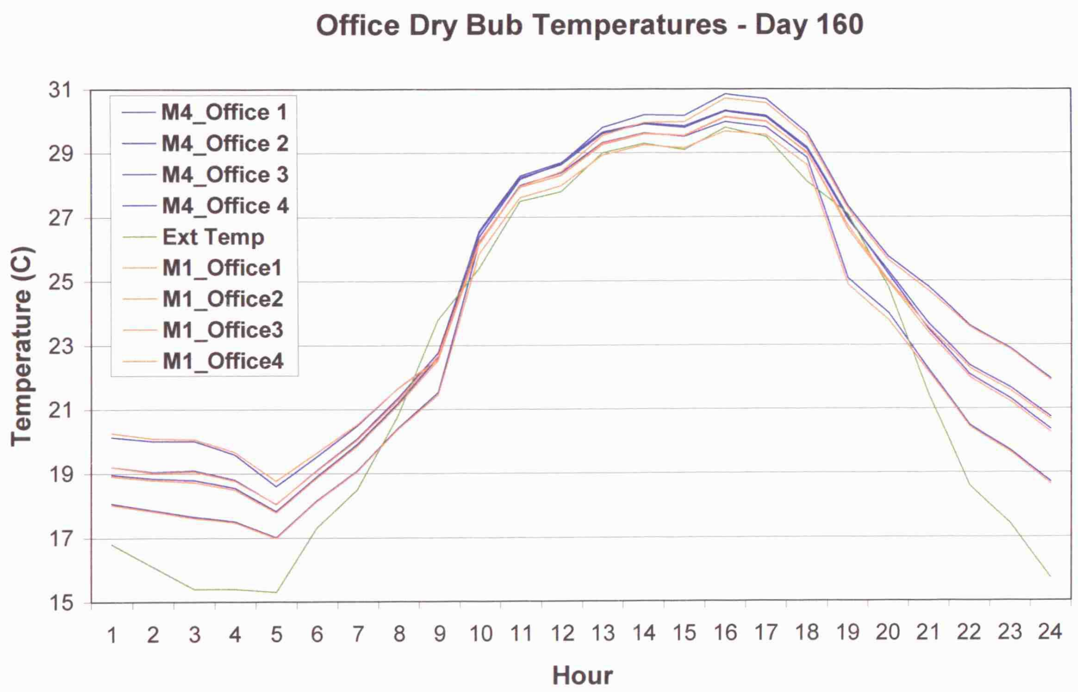
Investigation 4	Increase top chimney aperture (outlet) 50%
Simulation models	**Features/ Description**
Model 1	Basic solar chimney model
Model 3	Model 1, > 50% top chimney outlet
Simulation Results	

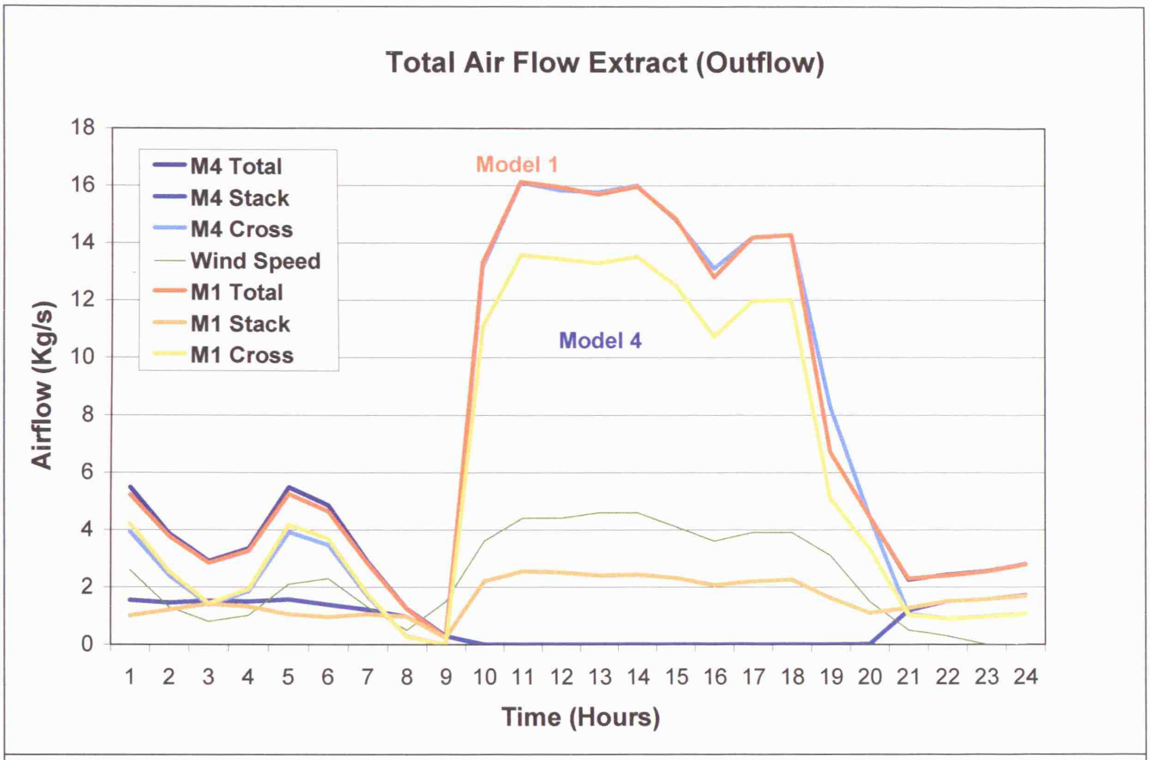


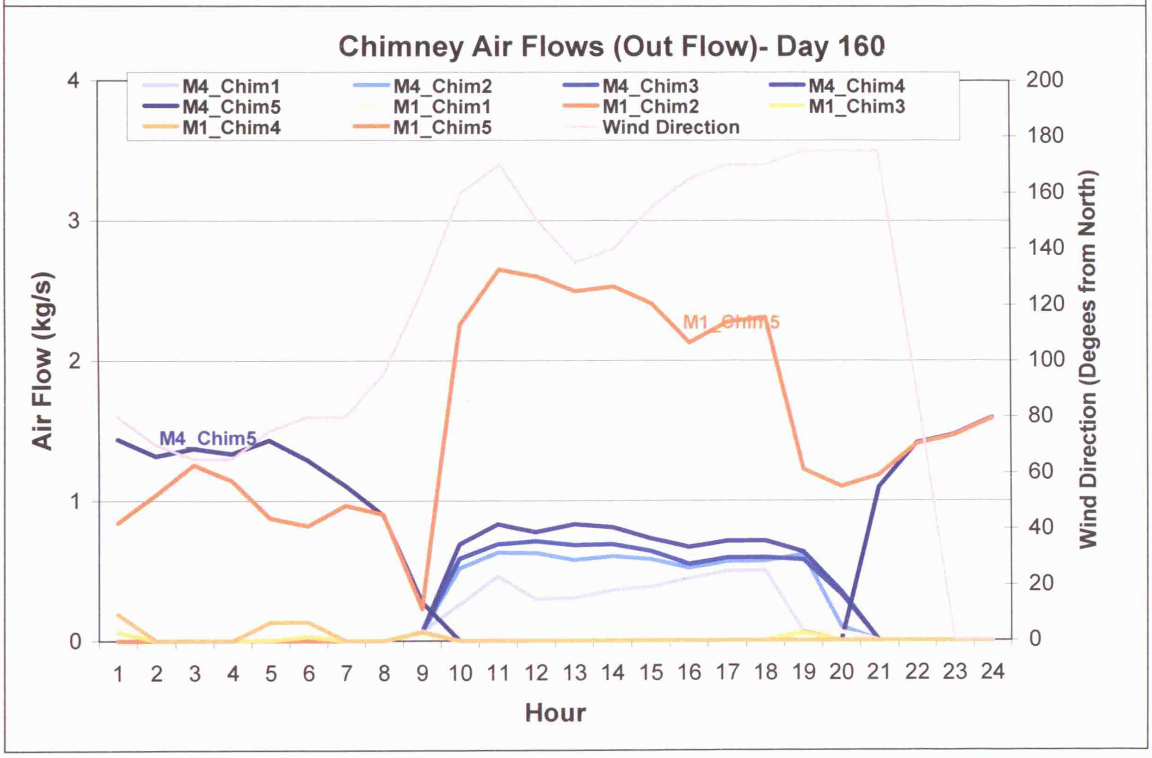


Investigation 5	Chimney outlet orientation
Simulation models	**Description / Features**
Model 1	Basic solar chimney model (North)
Model 4	Model 1, south orientation (prevailing wind)
Simulation Results	

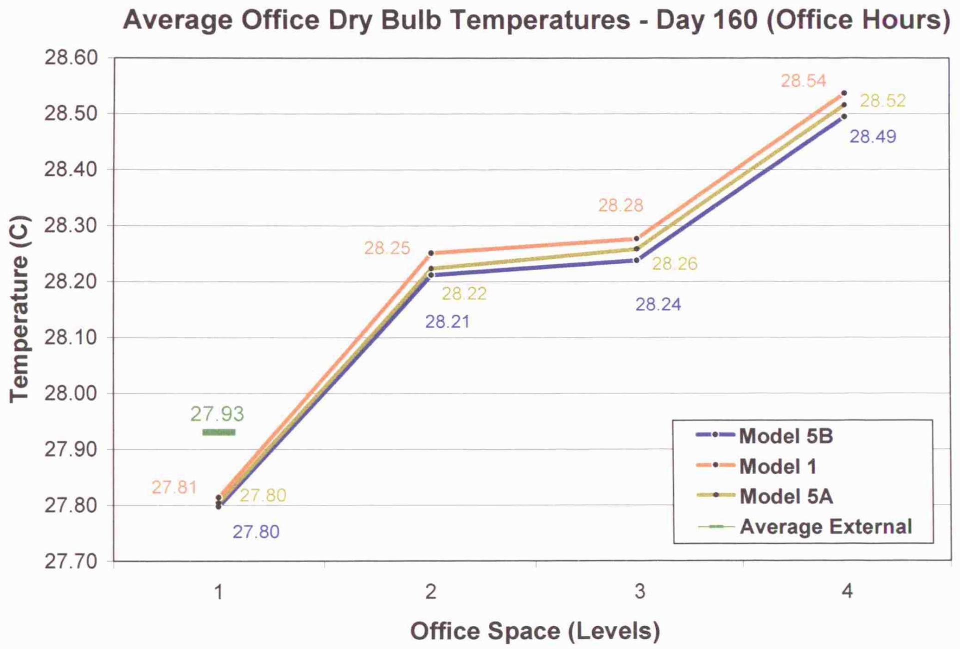


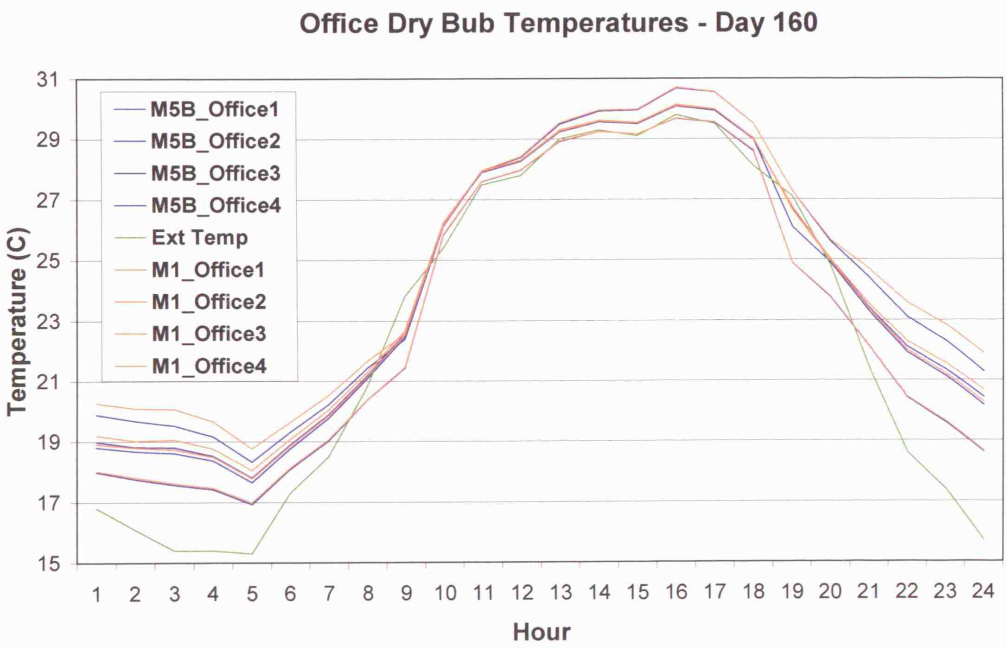


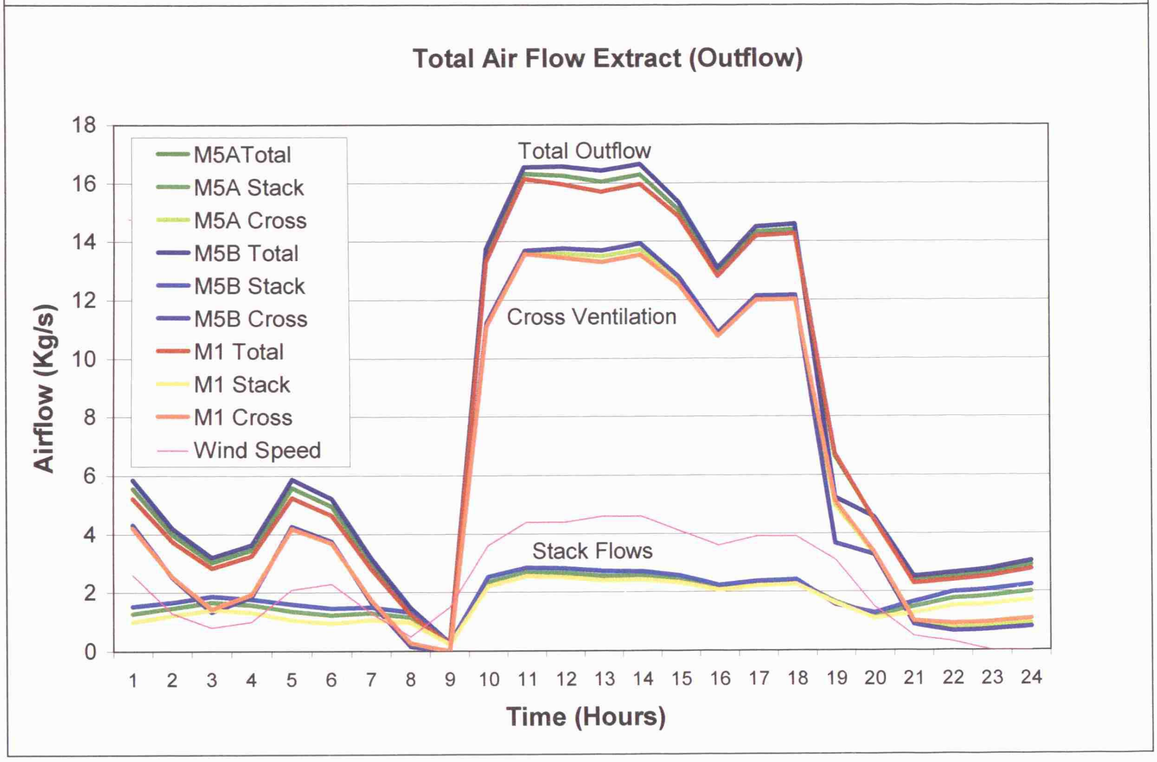

Total Air Flow Extract (Outflow)
M4 Total
M4 Stack
M4 Cross
Wind Speed
M1 Total
M1 Stack
M1 Cross
Model 1
Model 4
Airflow (Kg/s)
Time (Hours)


Chimney Air Flows (Out Flow)- Day 160
M4_Chim1
M4_Chim2
M4_Chim3
M4_Chim4
M4_Chim5
M1_Chim1
M1_Chim2
M1_Chim3
M1_Chim4
M1_Chim5
Wind Direction
M4_Chim5
M1_Chim5
Air Flow (kg/s)
Wind Direction (Degees from North)
Hour

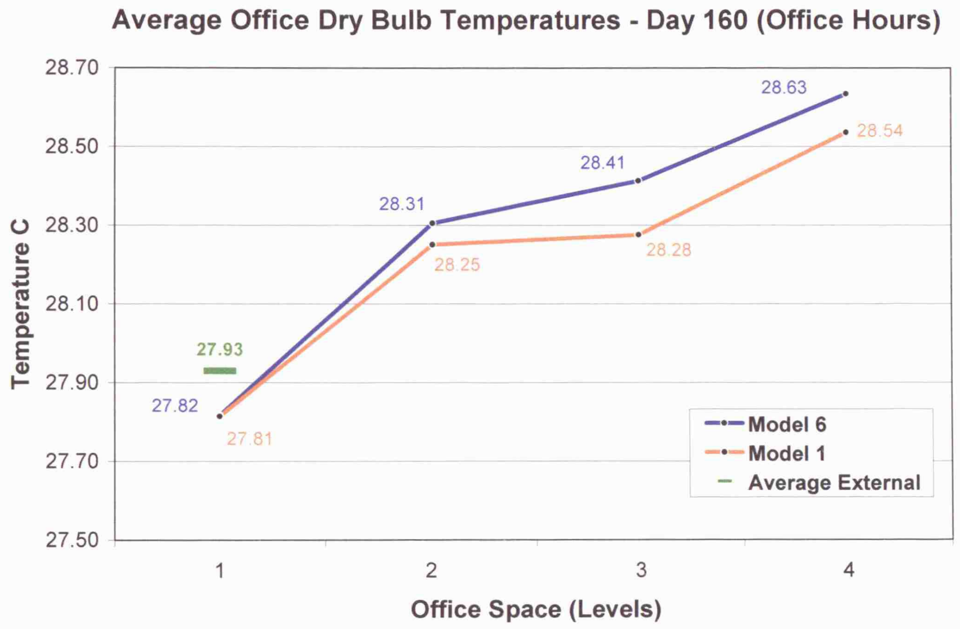
Investigation 6	Increase chimney height, stack effect
Simulation models	**Description / Features**
Model 1	Basic solar chimney model, 6m above roof
Model 5A	Model 1> 50% chimney height (9m)
Model 5B	Model 1> 100% chimney height (12m)
Simulation Results	

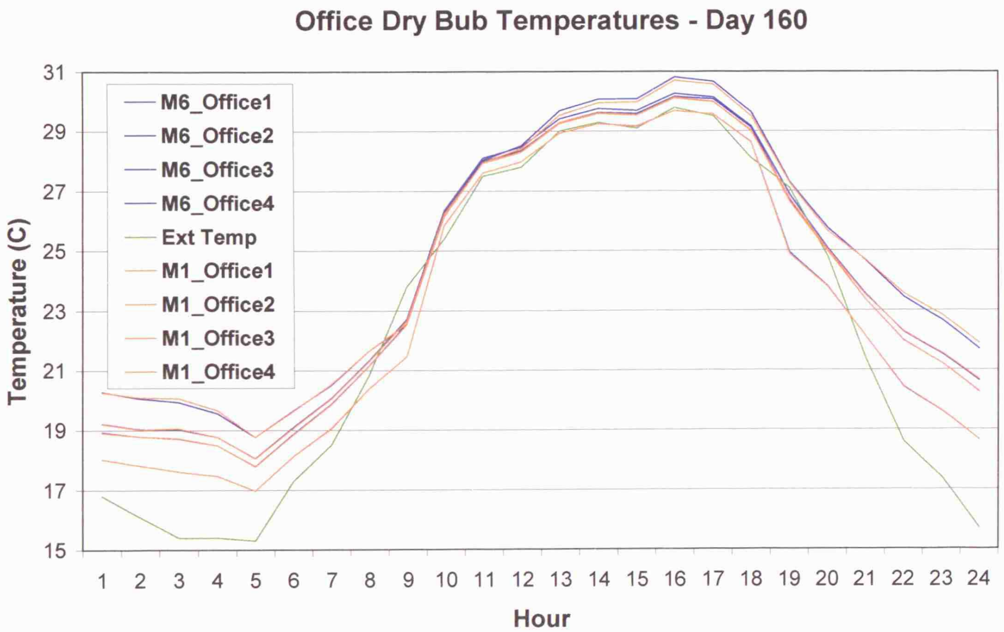


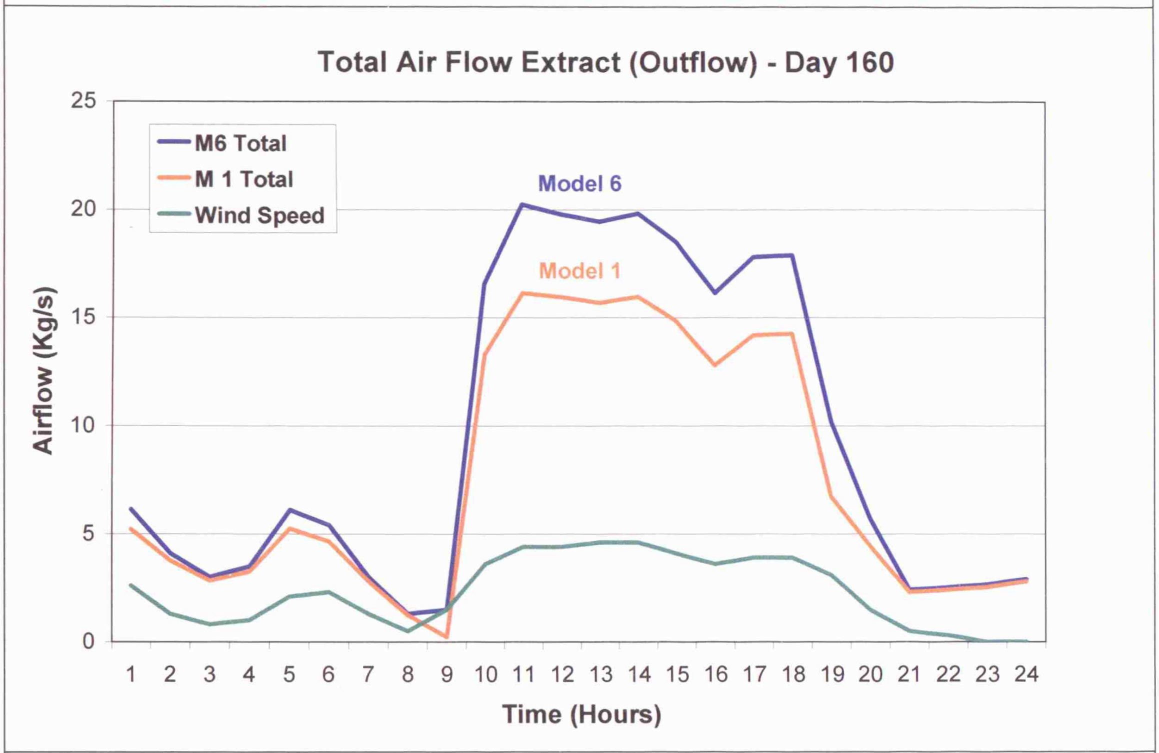


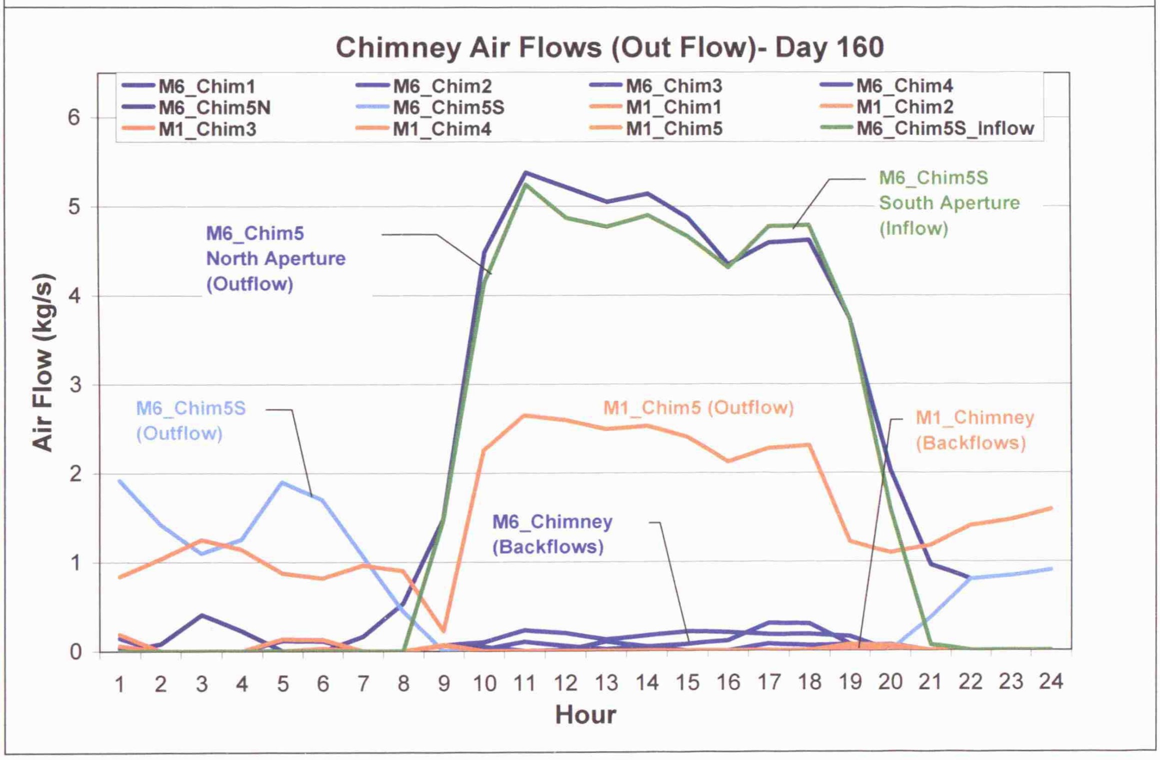

Total Air Flow Extract (Outflow)
Airflow (Kg/s)
Time (Hours)
M5ATotal
M5A Stack
M5A Cross
M5B Total
M5B Stack
M5B Cross
M1 Total
M1 Stack
M1 Cross
Wind Speed
Total Outflow
Cross Ventilation
Stack Flows
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Investigation 7	2 top chimney outlets, north + south
Simulation models	
Model 1	Basic solar chimney model (North)
Model 6	Model 1 + south aperture
Model 6S*	Model 6, sheltered (still day)
* Results for Model 6S are displayed in the overall model graphs for clarity	
Simulation Results	

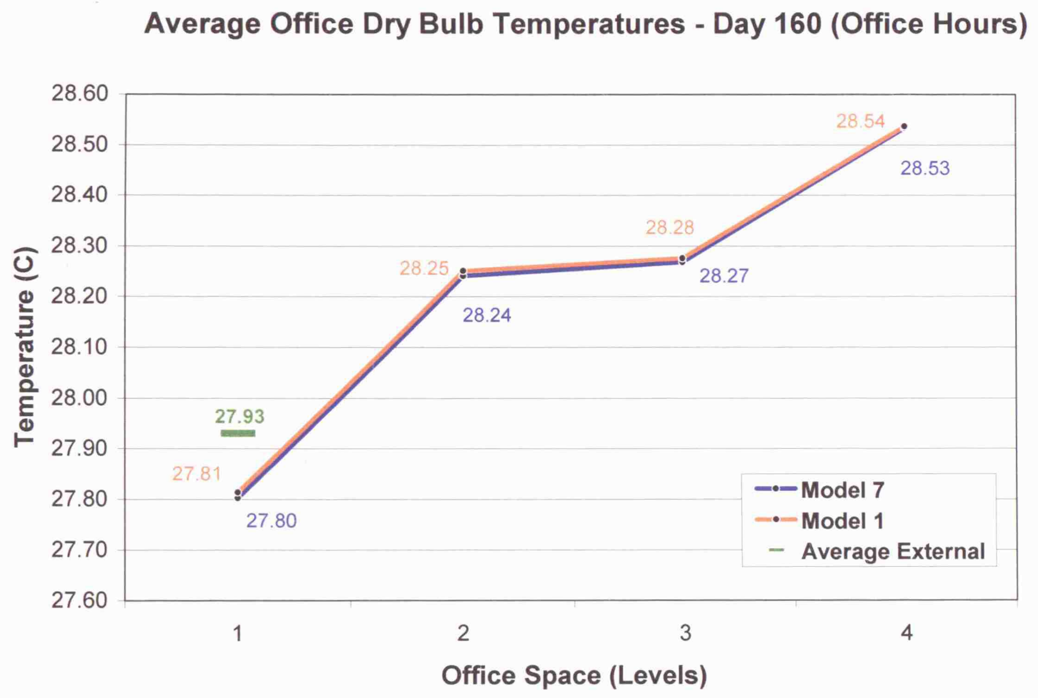


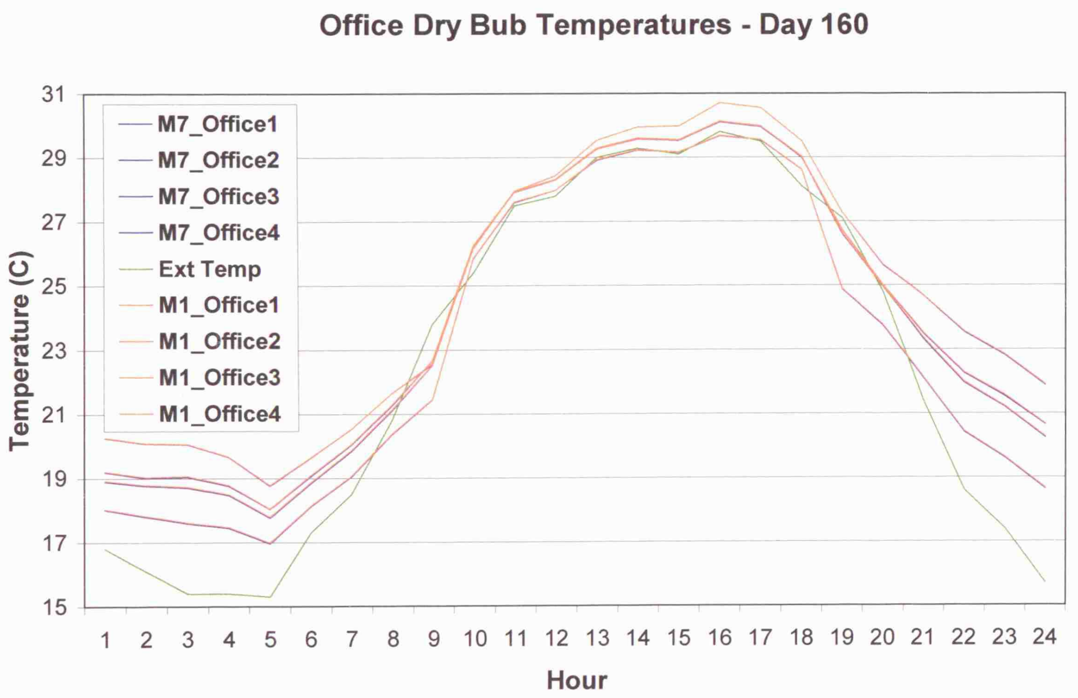


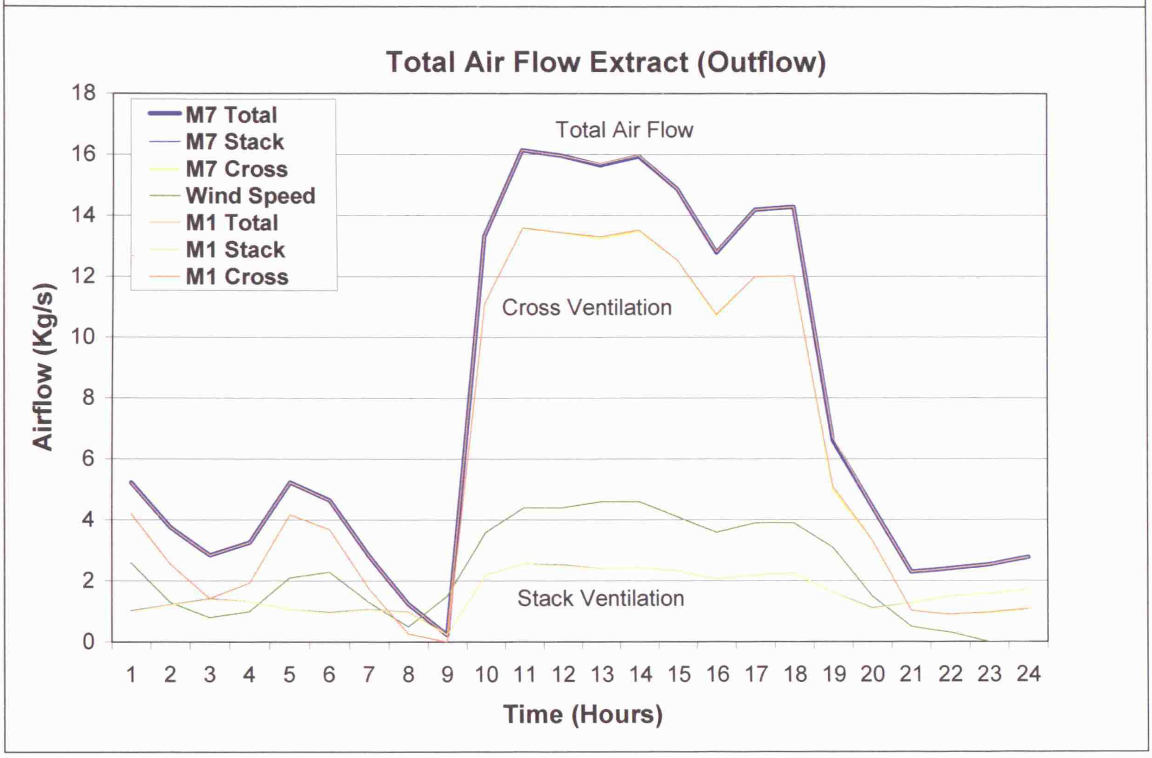

Total Air Flow Extract (Outflow) - Day 160
M6 Total
M 1 Total
Wind Speed
Model 6
Model 1
Airflow (Kg/s)
0
5
10
15
20
25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (Hours)


Chimney Air Flows (Out Flow)- Day 160
M6_Chim1
M6_Chim2
M6_Chim3
M6_Chim4
M6_Chim5N
M6_Chim5S
M1_Chim1
M1_Chim2
M1_Chim3
M1_Chim4
M1_Chim5
M6_Chim5S_Inflow
M6_Chim5 North Aperture (Outflow)
M6_Chim5S South Aperture (Inflow)
M6_Chim5S (Outflow)
M1_Chim5 (Outflow)
M1_Chimney (Backflows)
M6_Chimney (Backflows)
Air Flow (kg/s)
0
1
2
3
4
5
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour

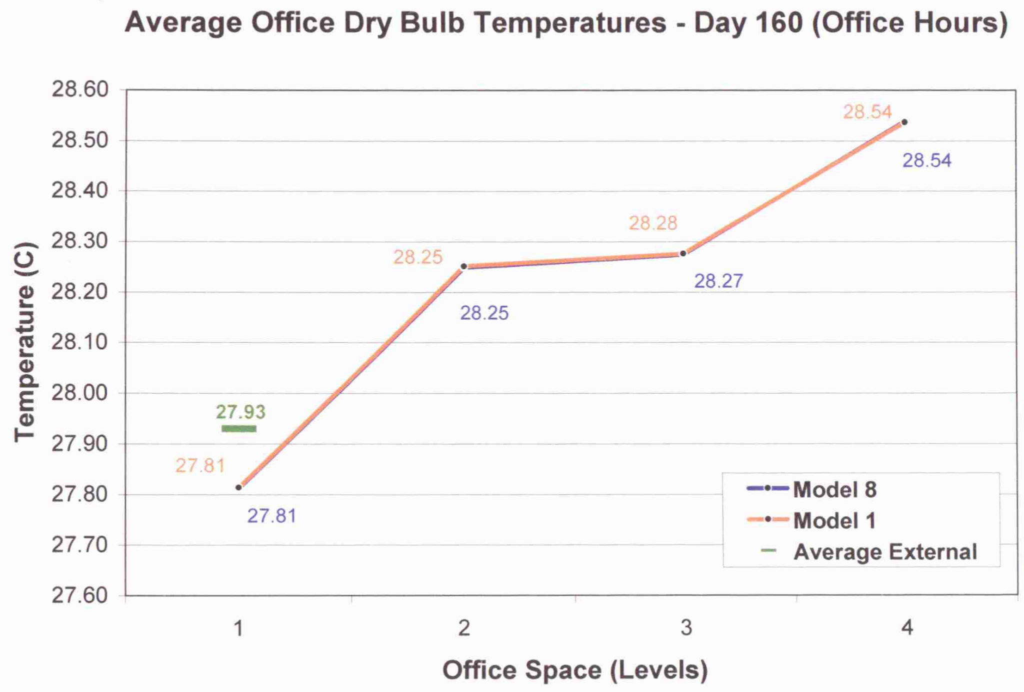
Investigation 8	Increase chimney insulation
Simulation models	Features / Desctiption
Model 1	Basic solar chimney model (50mm)
Model 7	Model , insulation: 200mm
Simulation Results	

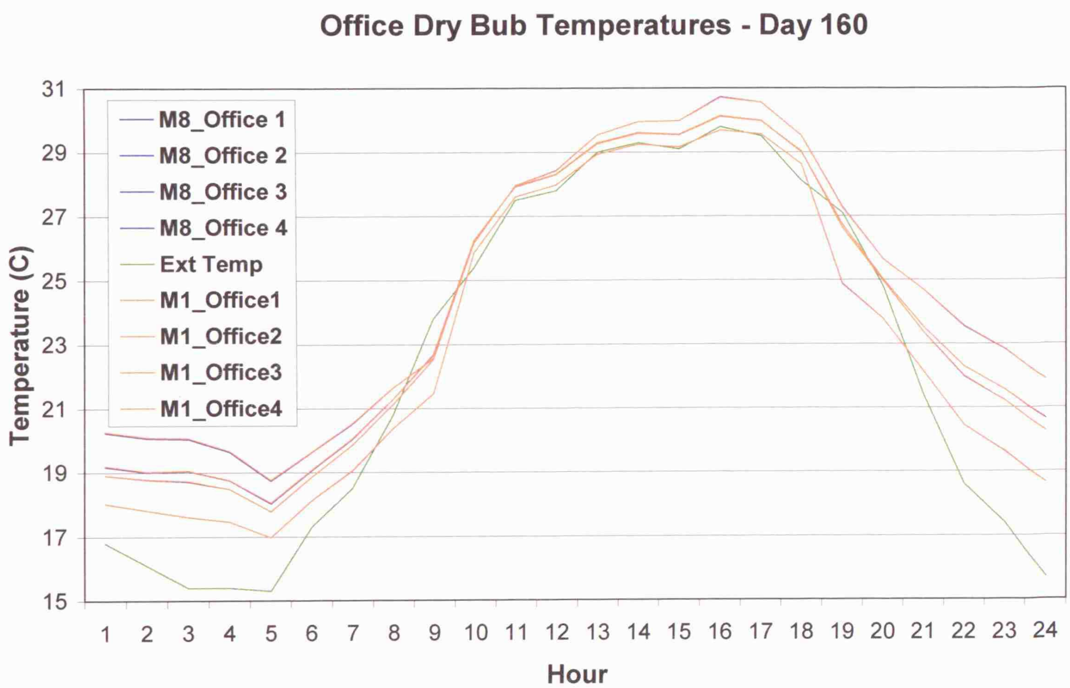


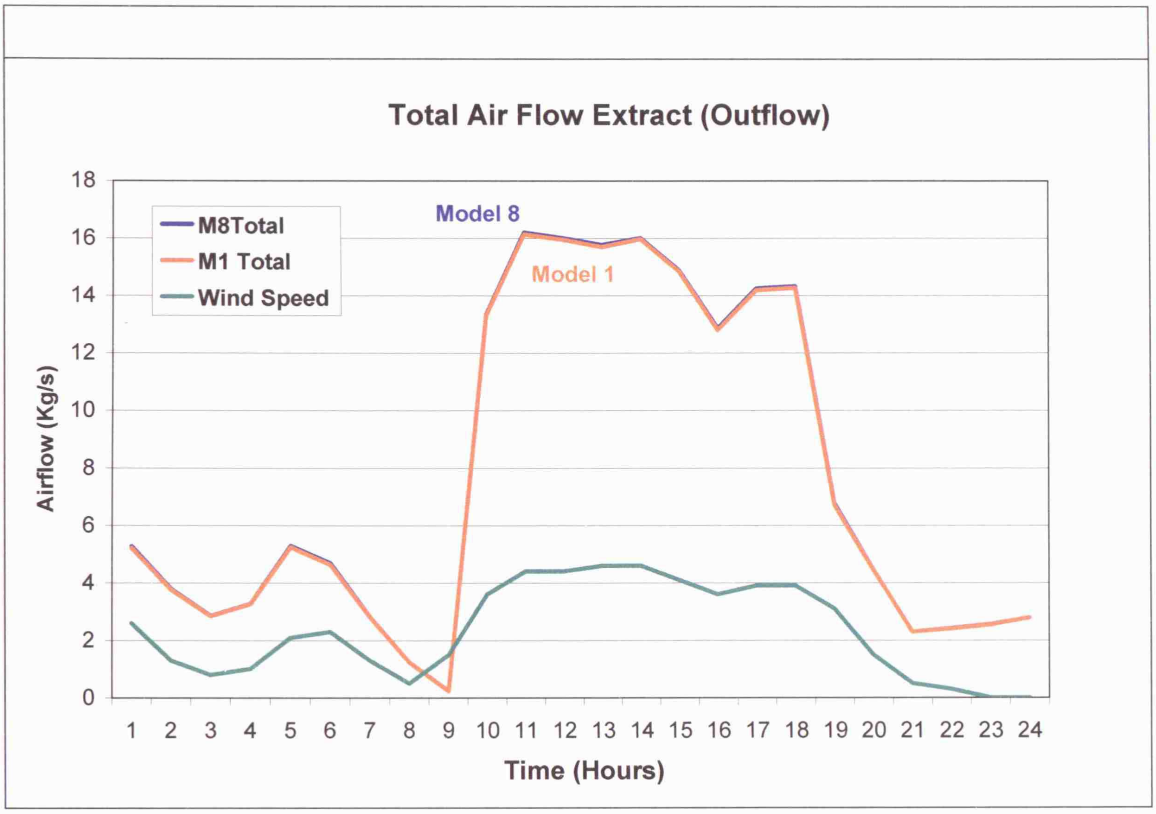



Total Air Flow Extract (Outflow)
M7 Total
M7 Stack
M7 Cross
Wind Speed
M1 Total
M1 Stack
M1 Cross
Total Air Flow
Cross Ventilation
Stack Ventilation
Airflow (Kg/s)
Time (Hours)
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

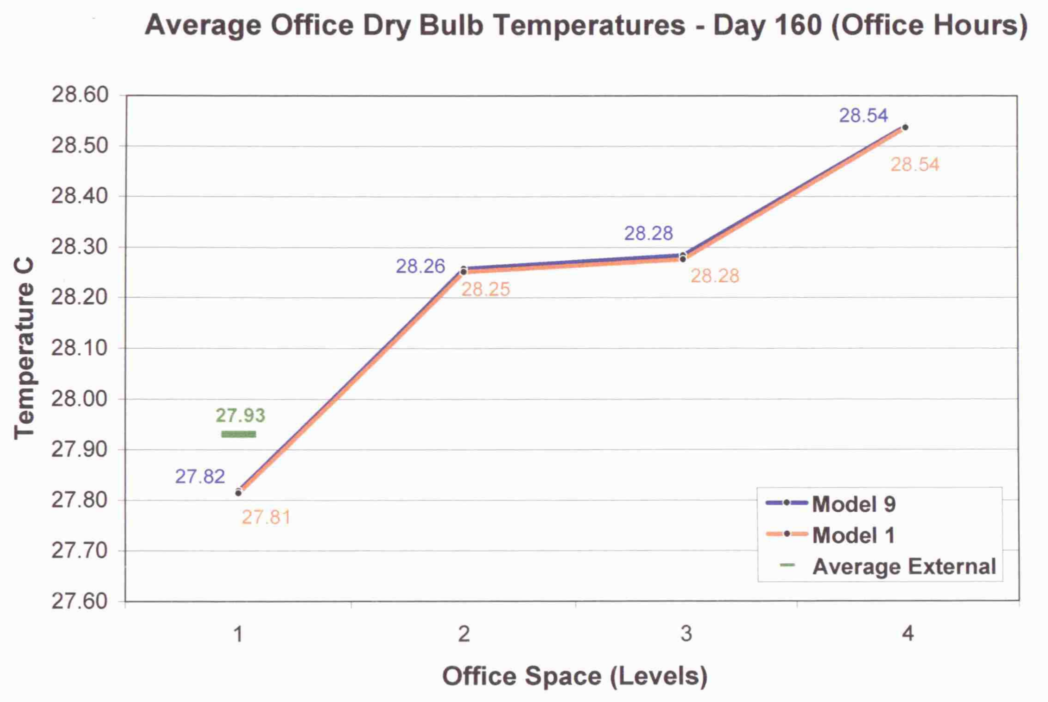
Investigation 9	Sloped chimney top, improve air flow
Simulation models	Features / Description
Model 1	Basic solar chimney model, flat top
Model 8	Model 1, sloped top, aperture location
Simulation Results	

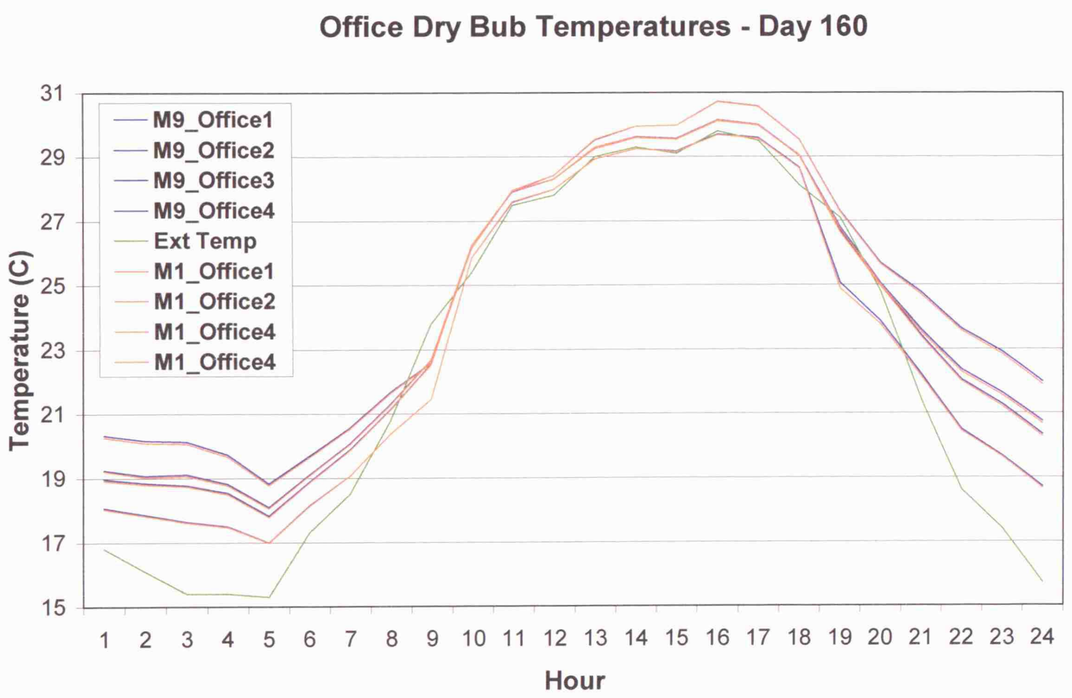


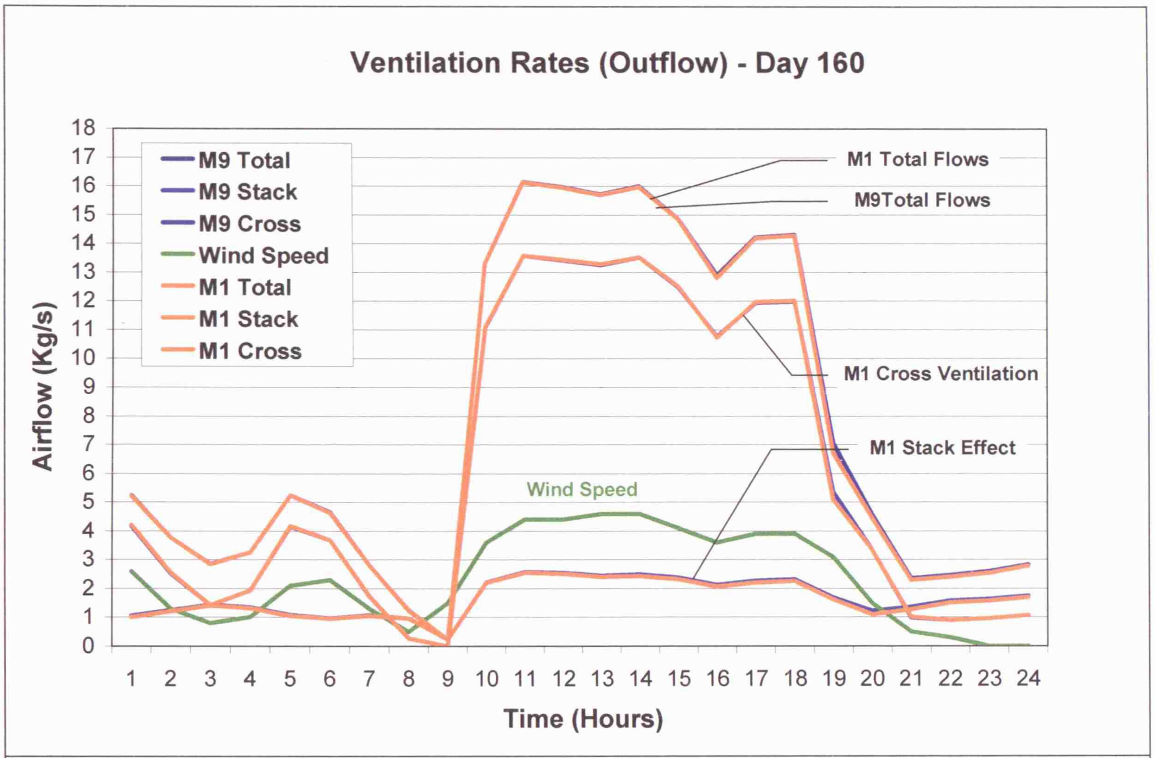


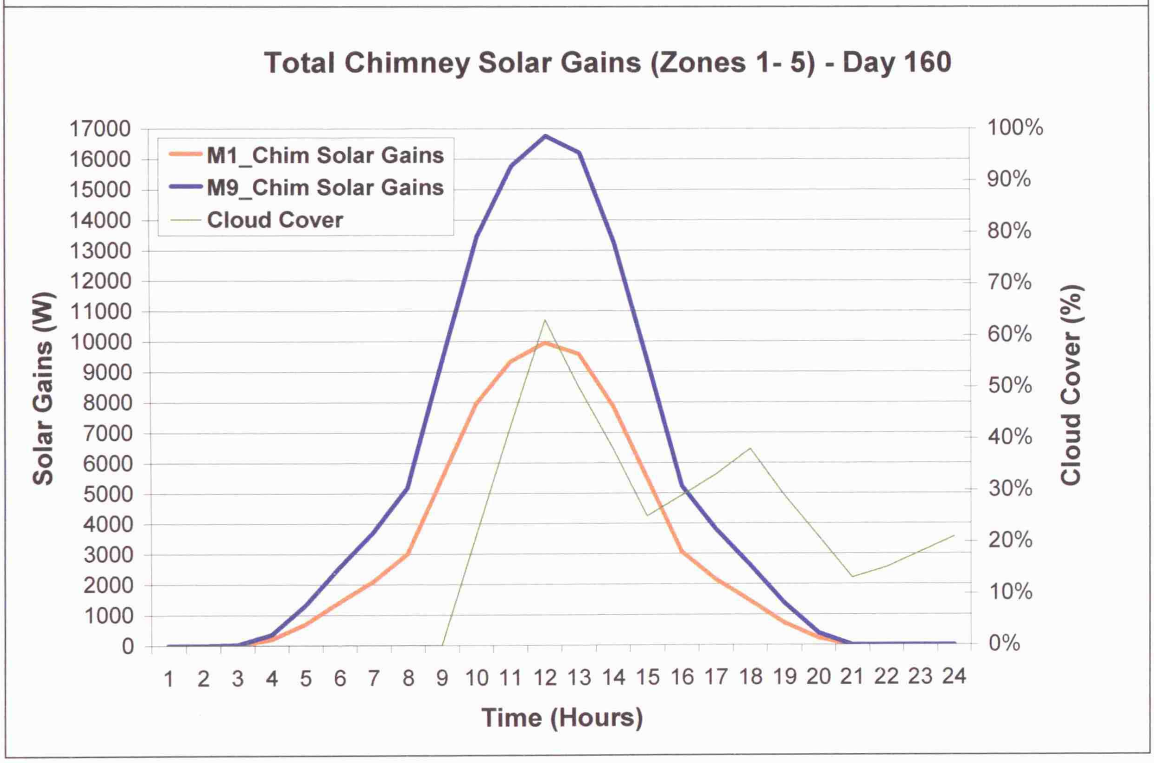

Total Air Flow Extract (Outflow)
Airflow (Kg/s)
Time (Hours)
M8Total
M1 Total
Wind Speed
Model 8
Model 1
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Investigation 10	Increase chimney absorptance
Simulation models	Features / Description
Model 1	Basic solar chimney model, (α:0,4)
Model 9	Model1 > absorptance (α:0,9)
Simulation Results	

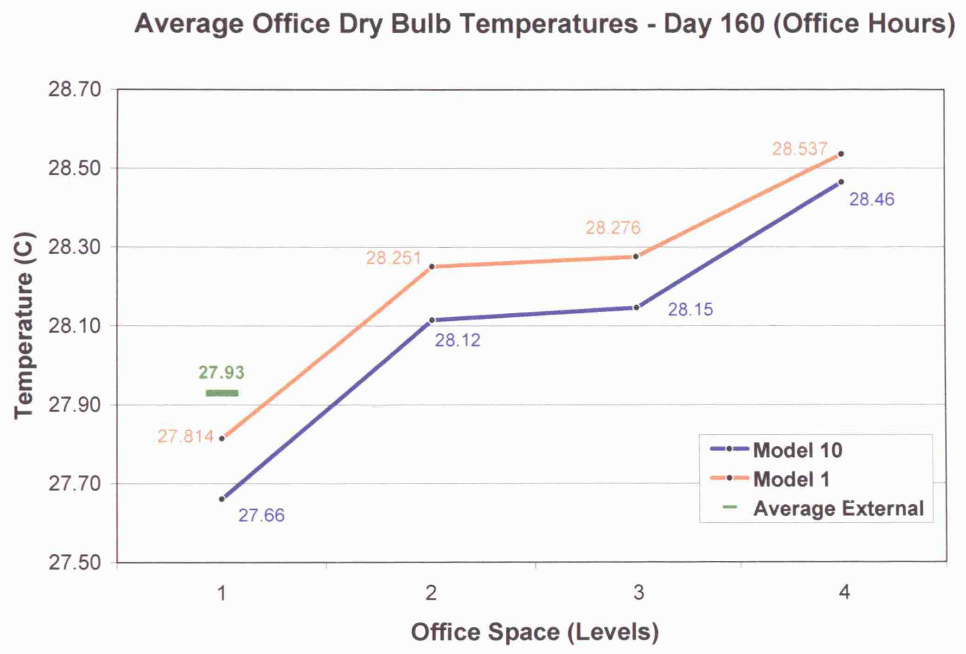


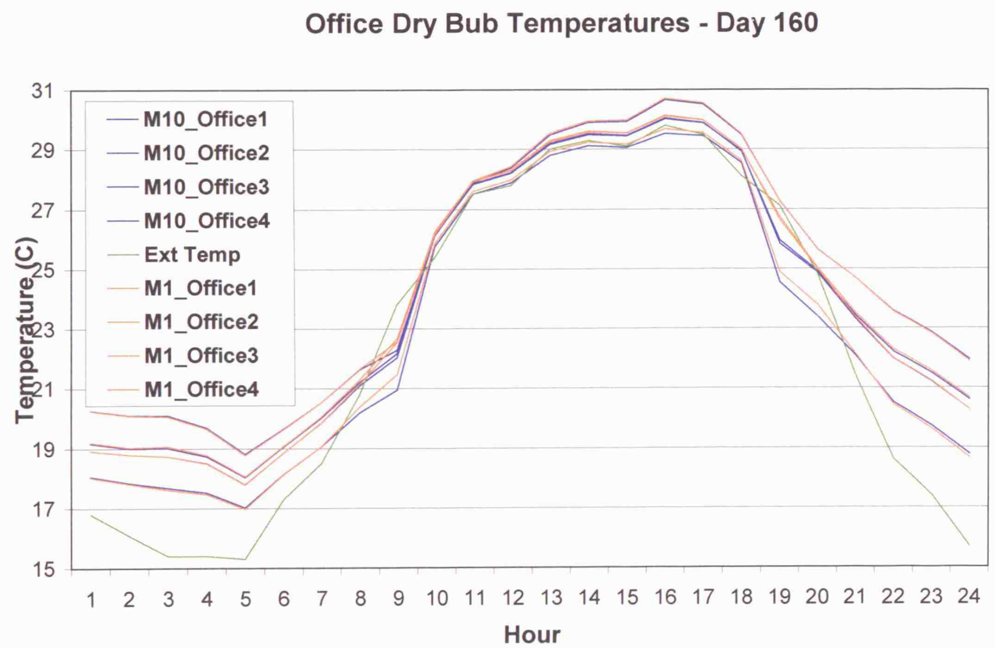


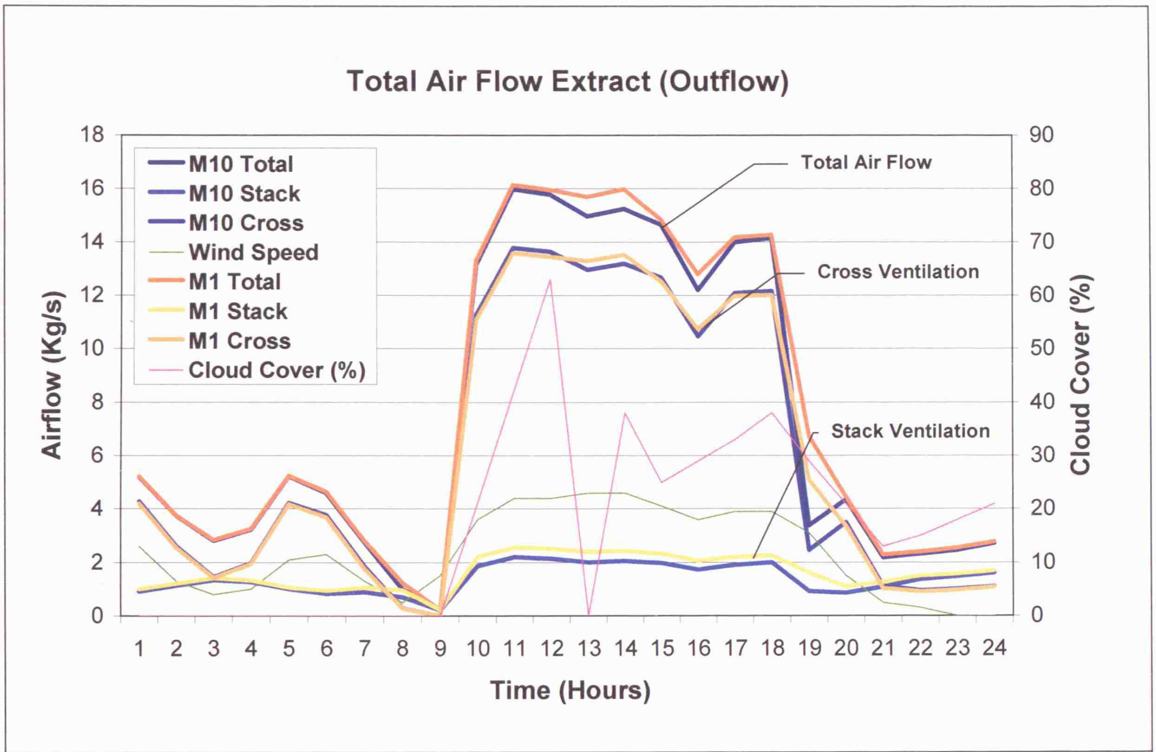

Ventilation Rates (Outflow) - Day 160
Airflow (Kg/s)
Time (Hours)
M9 Total
M9 Stack
M9 Cross
Wind Speed
M1 Total
M1 Stack
M1 Cross
M1 Total Flows
M9Total Flows
M1 Cross Ventilation
M1 Stack Effect
Wind Speed

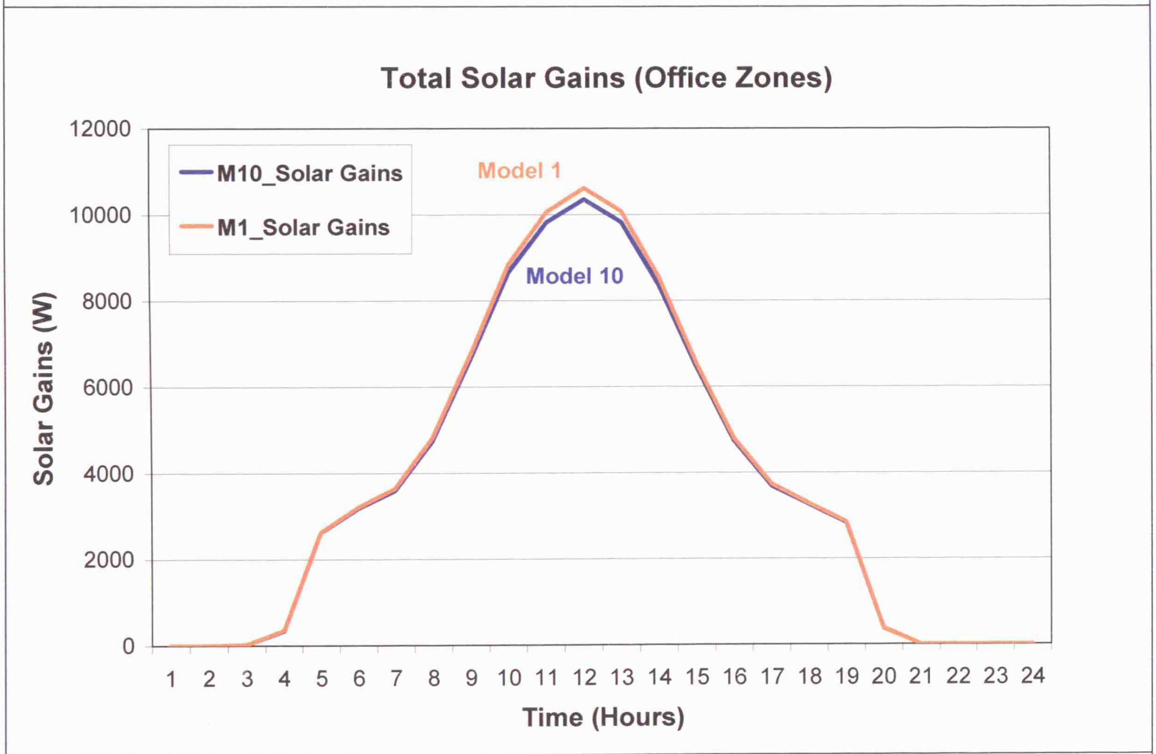

Total Chimney Solar Gains (Zones 1- 5) - Day 160
Solar Gains (W)
Cloud Cover (%)
Time (Hours)
M1_Chim Solar Gains
M9_Chim Solar Gains
Cloud Cover

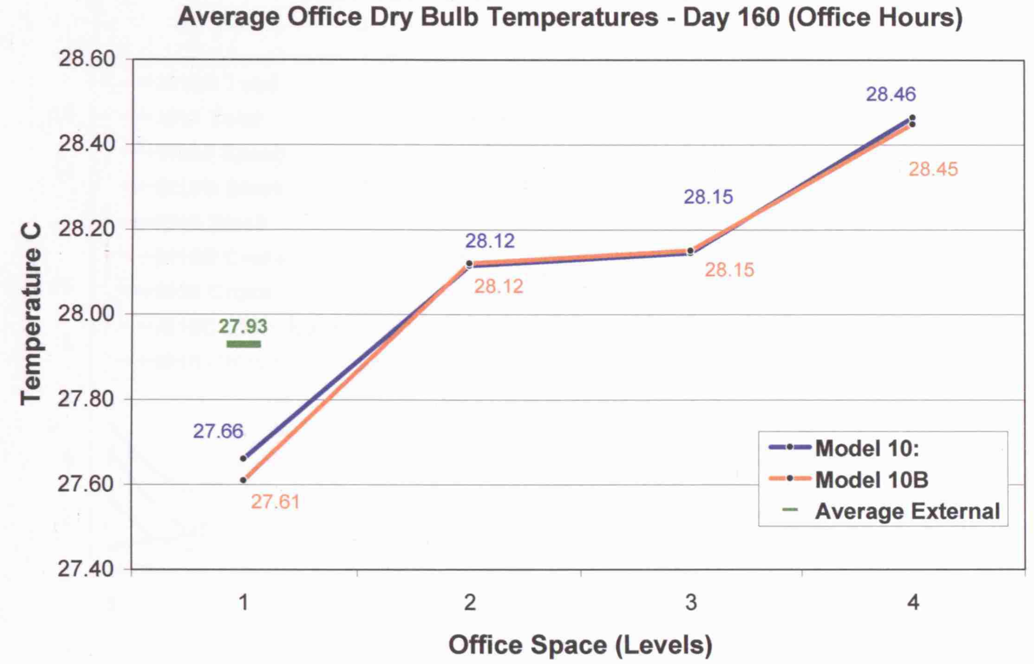
Investigation 11	Central chimney location, reduce solar gains
Simulation models	**Features / Description**
Model 1	Basic solar chimney model, (max sun)
Model 10	Model 1, only top part exposed to sun
Model 10B*	Model 10 > 50% top chimney outlet
* Comparison between Model1 and Model 10B follow separately for clarity	
Simulation Results	

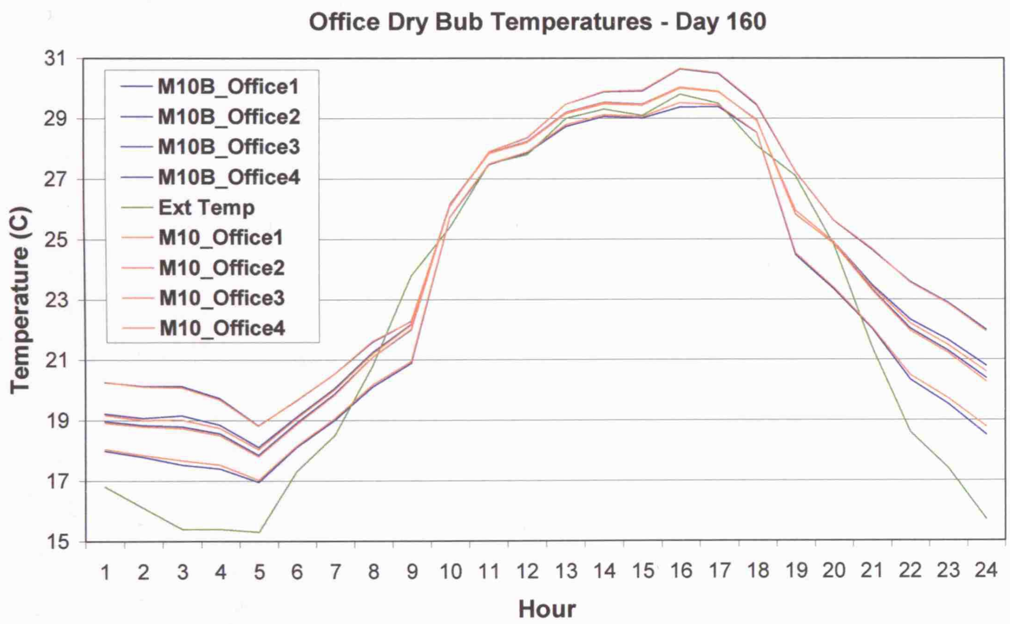


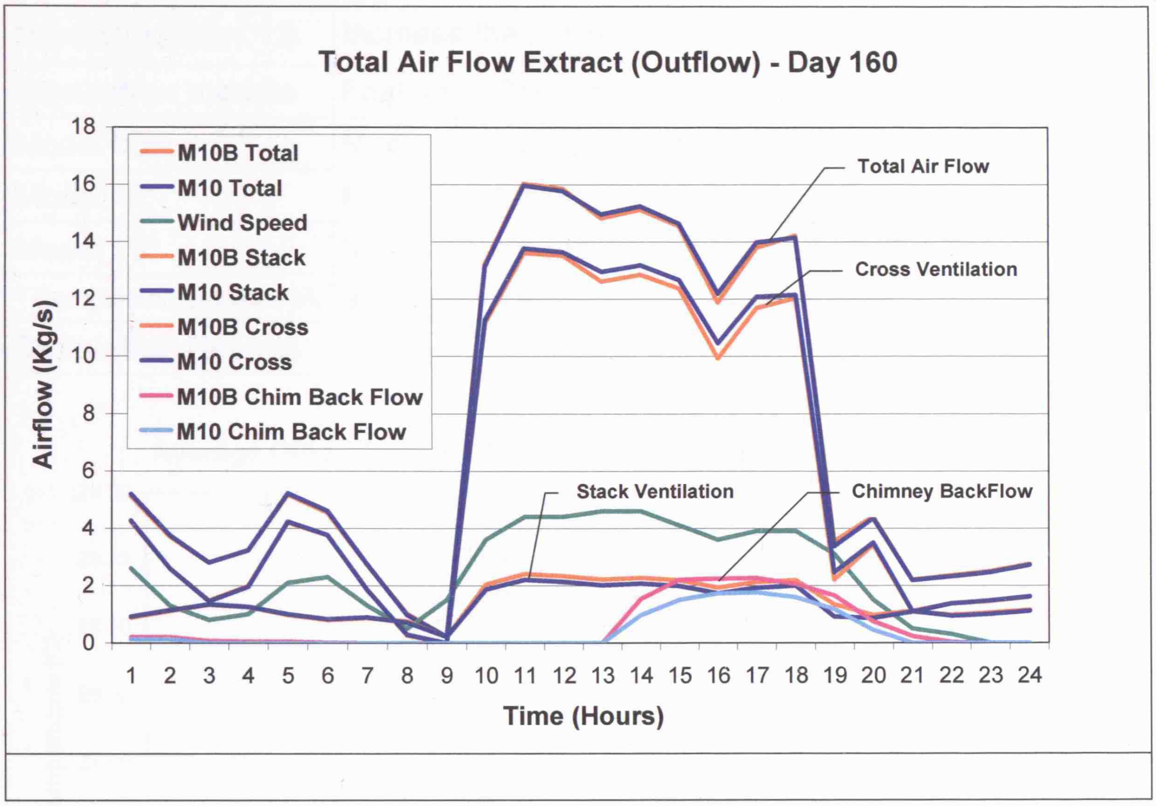



Total Air Flow Extract (Outflow)
M10 Total
M10 Stack
M10 Cross
Wind Speed
M1 Total
M1 Stack
M1 Cross
Cloud Cover (%)
Total Air Flow
Cross Ventilation
Stack Ventilation
Airflow (Kg/s)
Cloud Cover (%)
Time (Hours)
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
80
90
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

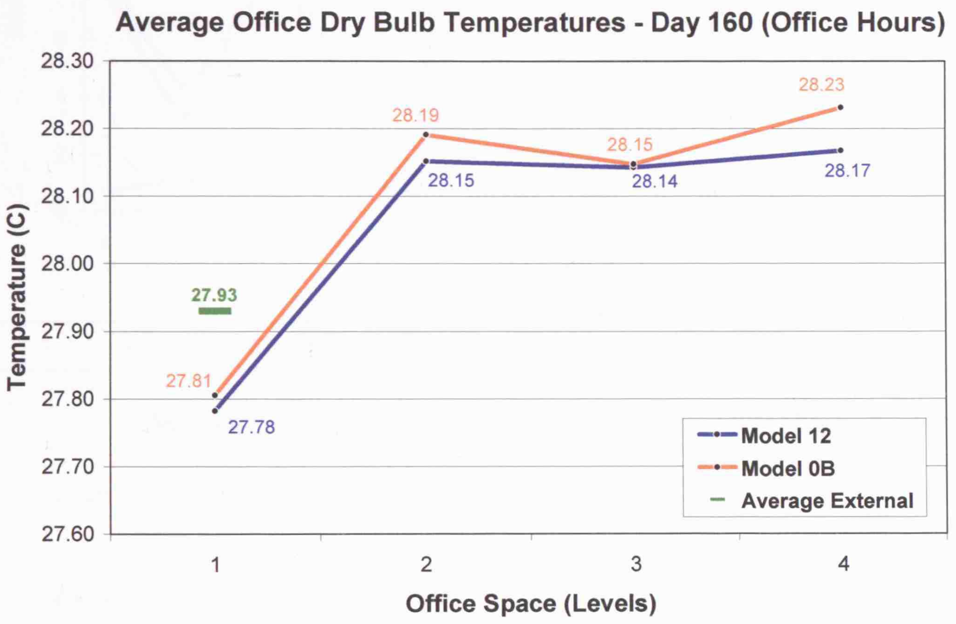

Total Solar Gains (Office Zones)
M10_Solar Gains
M1_Solar Gains
Model 1
Model 10
Solar Gains (W)
Time (Hours)
0
2000
4000
6000
8000
10000
12000
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

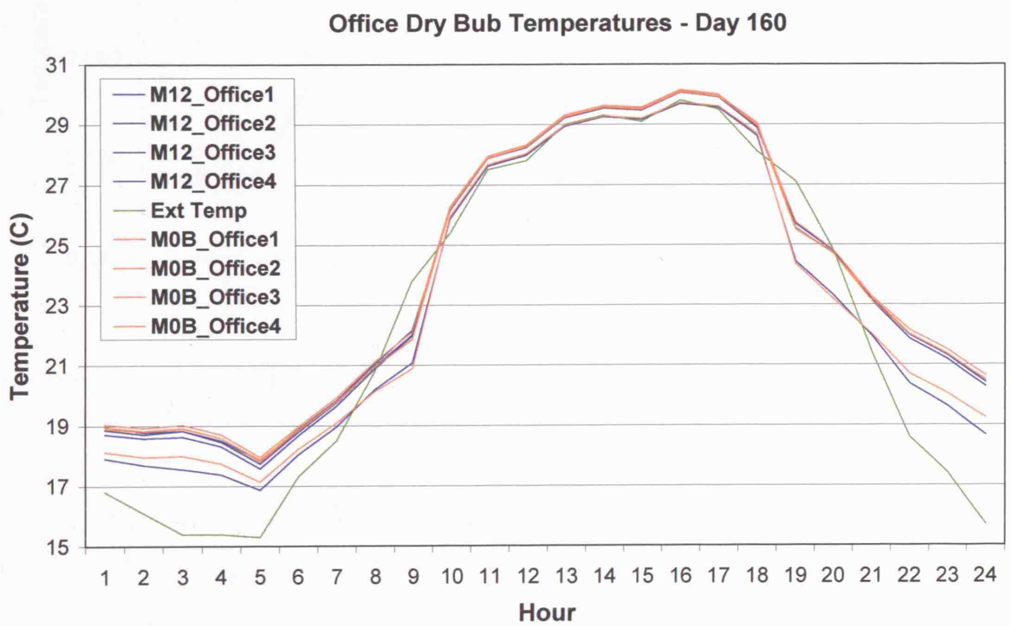

Average Office Dry Bulb Temperatures - Day 160 (Office Hours)
Temperature C
28.60
28.40
28.20
28.00
27.80
27.60
27.40
28.46
28.45
28.15
28.15
28.12
28.12
27.93
27.66
27.61
1
2
3
4
Office Space (Levels)
Model 10:
Model 10B
Average External

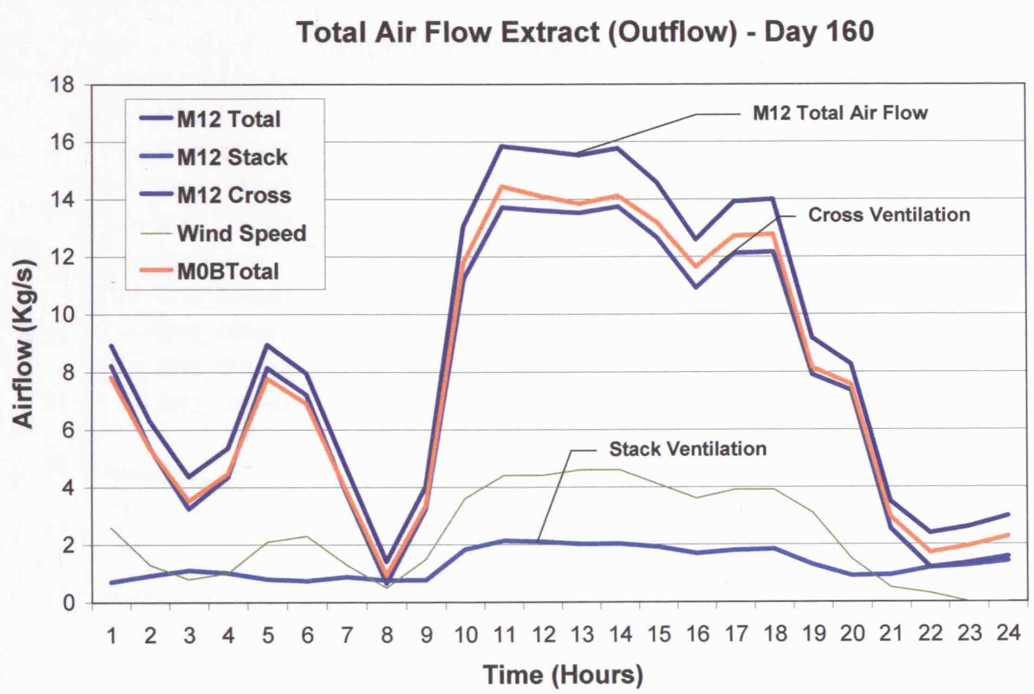

Office Dry Bub Temperatures - Day 160
Temperature (C)
31
29
27
25
23
21
19
17
15
M10B_Office1
M10B_Office2
M10B_Office3
M10B_Office4
Ext Temp
M10_Office1
M10_Office2
M10_Office3
M10_Office4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour

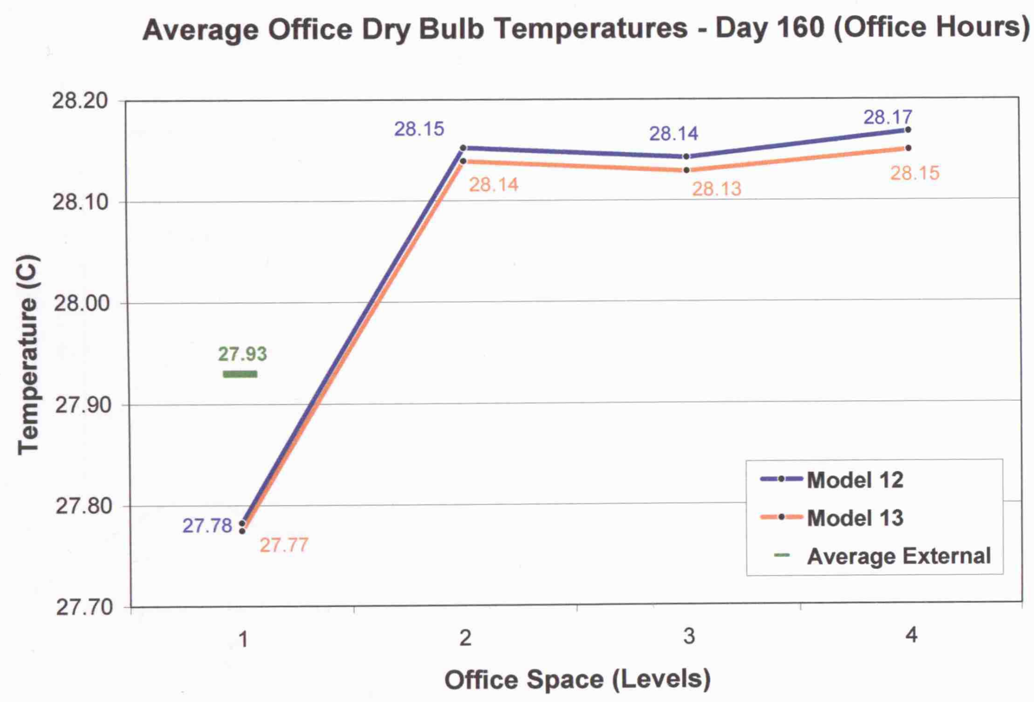

Total Air Flow Extract (Outflow) - Day 160
Airflow (Kg/s)
0
2
4
6
8
10
12
14
16
18
M10B Total
M10 Total
Wind Speed
M10B Stack
M10 Stack
M10B Cross
M10 Cross
M10B Chim Back Flow
M10 Chim Back Flow
Total Air Flow
Cross Ventilation
Stack Ventilation
Chimney BackFlow
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (Hours)

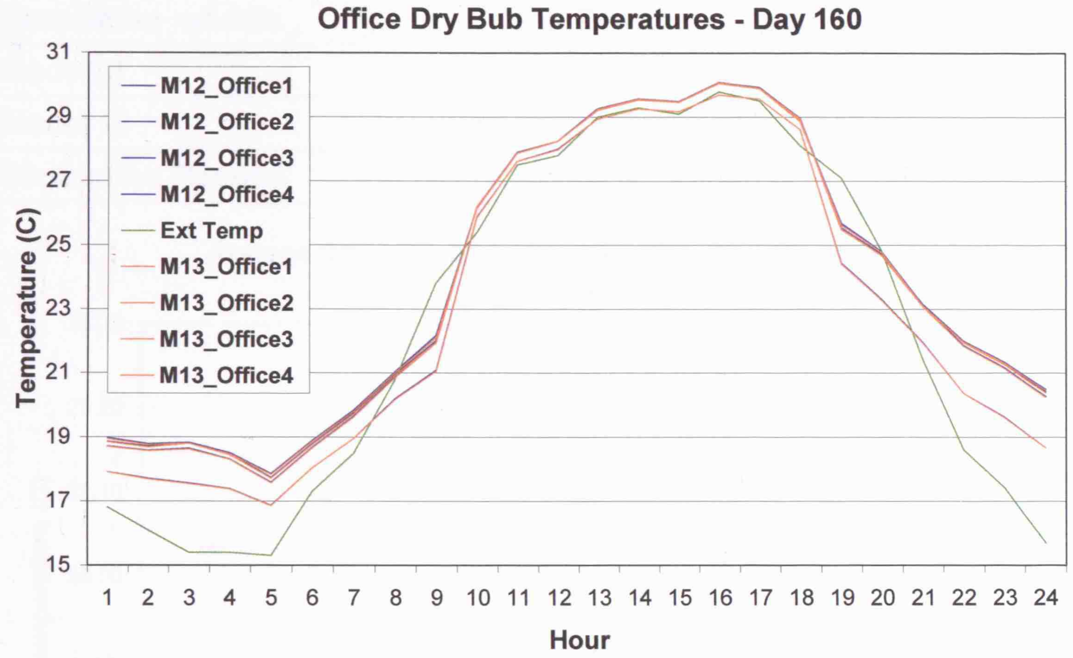
Investigation 12	Increase thermal mass, night cooling / cool storage
Simulation models	Features / Description
Model 0B	Model 0 + double concrete floors
Model 12*	Mode 1, double concrete floor
Model 13*	Model 12 > thermal mass (concrete fins)
* Comparison between Model 12 and Model 13 follow separately for clarity	
Simulation Results	

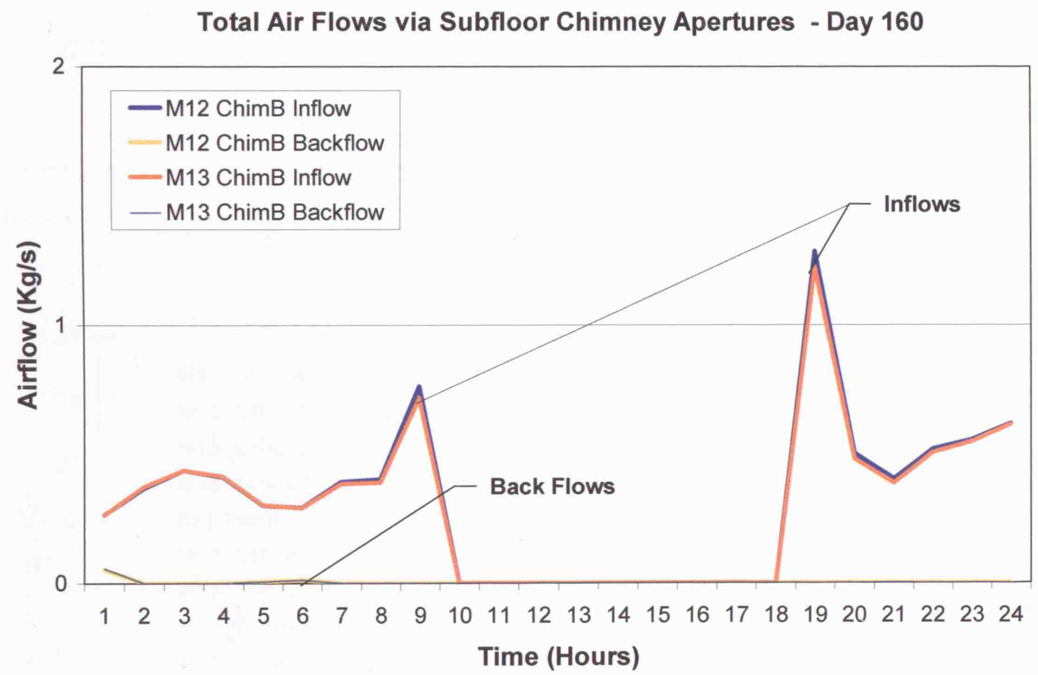




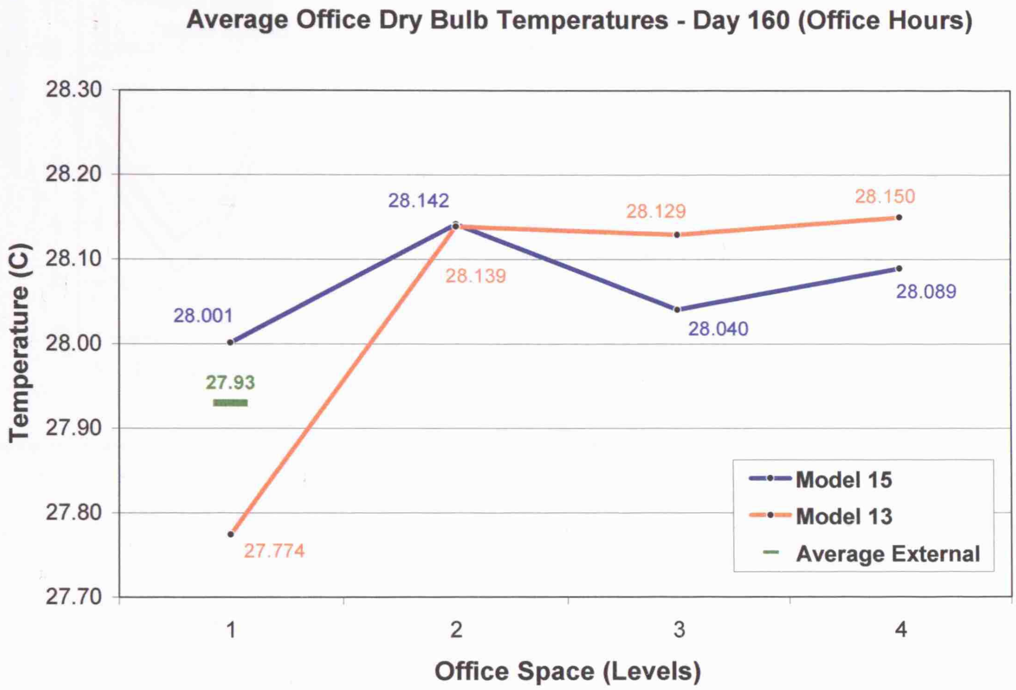

Total Air Flow Extract (Outflow) - Day 160
M12 Total
M12 Stack
M12 Cross
Wind Speed
M0BTotal
M12 Total Air Flow
Cross Ventilation
Stack Ventilation
Airflow (Kg/s)
Time (Hours)
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

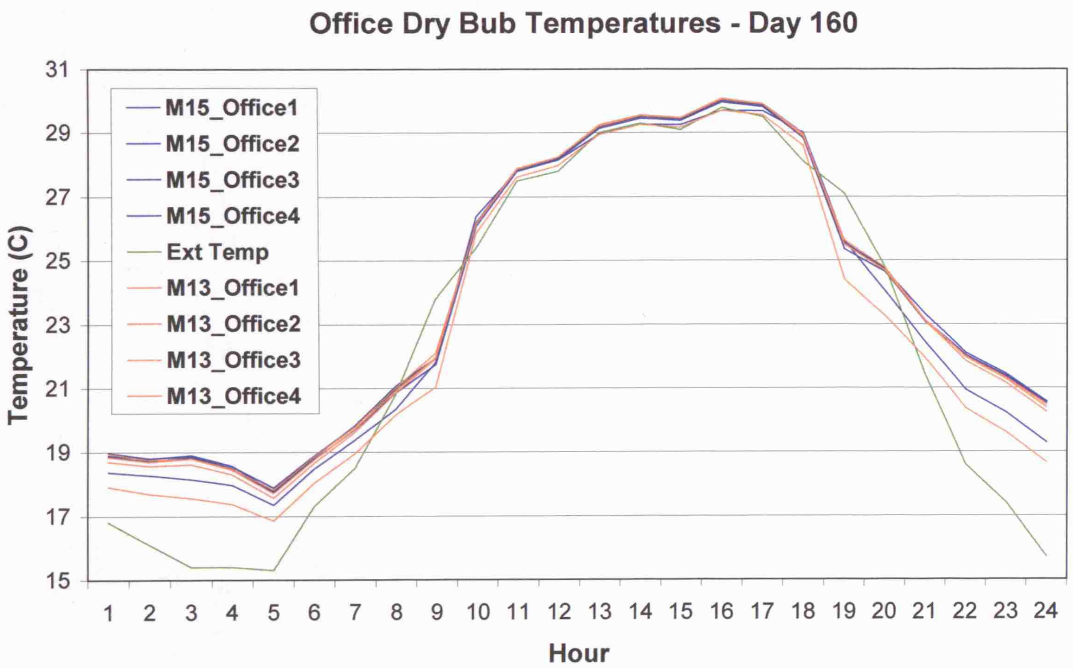

Average Office Dry Bulb Temperatures - Day 160 (Office Hours)
Temperature (C)
Office Space (Levels)
28.20
28.10
28.00
27.90
27.80
27.70
1
2
3
4
27.93
27.78
27.77
28.15
28.14
28.14
28.13
28.17
28.15
Model 12
Model 13
Average External

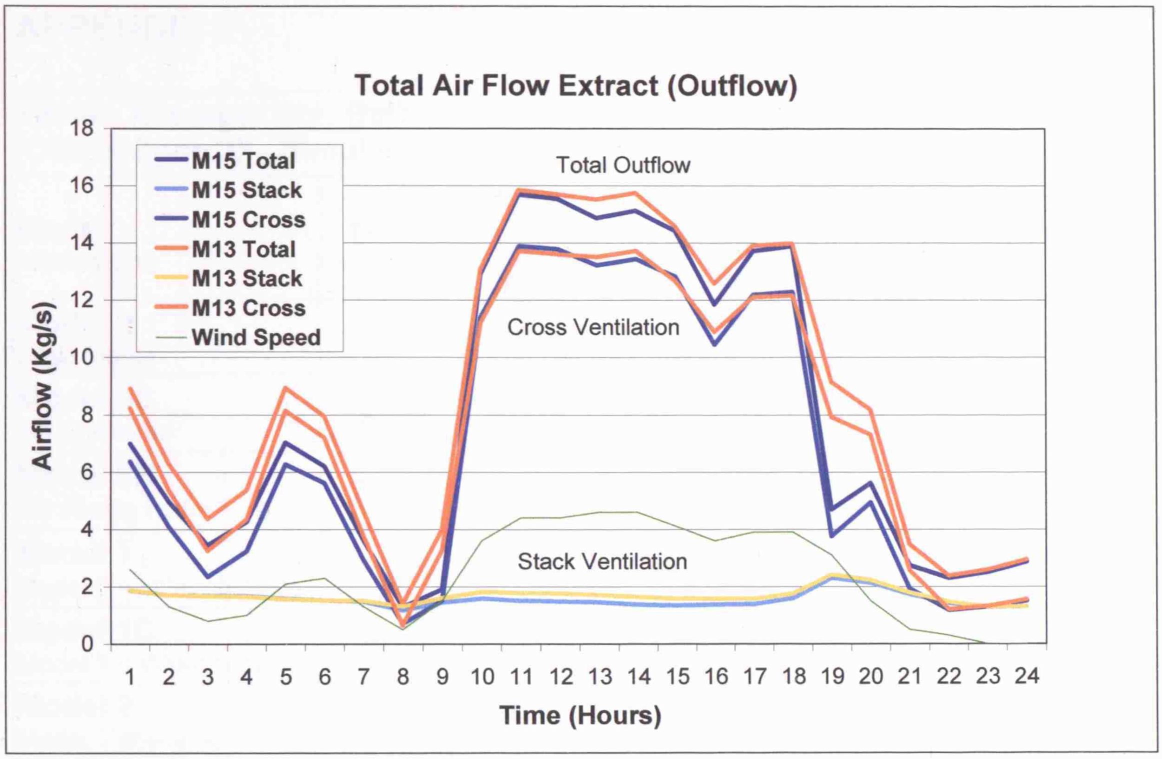

Office Dry Bub Temperatures - Day 160
Temperature (C)
Hour
M12_Office1
M12_Office2
M12_Office3
M12_Office4
Ext Temp
M13_Office1
M13_Office2
M13_Office3
M13_Office4
31
29
27
25
23
21
19
17
15
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24


Total Air Flows via Subfloor Chimney Apertures - Day 160
Airflow (Kg/s)
Time (Hours)
M12 ChimB Inflow
M12 ChimB Backflow
M13 ChimB Inflow
M13 ChimB Backflow
Inflows
Back Flows
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Investigation 13	Chimney location + thermal mass
Simulation models	Features / Description
Mode 13	Best case thermal mass model
Model 15	Model 13 +Model 10 combined
Simulation Results	






Total Air Flow Extract (Outflow)
M15 Total
M15 Stack
M15 Cross
M13 Total
M13 Stack
M13 Cross
Wind Speed
Total Outflow
Cross Ventilation
Stack Ventilation
Airflow (Kg/s)
Time (Hours)
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

APPENDIX 3

Table: Average Dry Bulb Temperatures and Air Flows for First Floor (Office/ Zone 2) – Simulation DAY 160

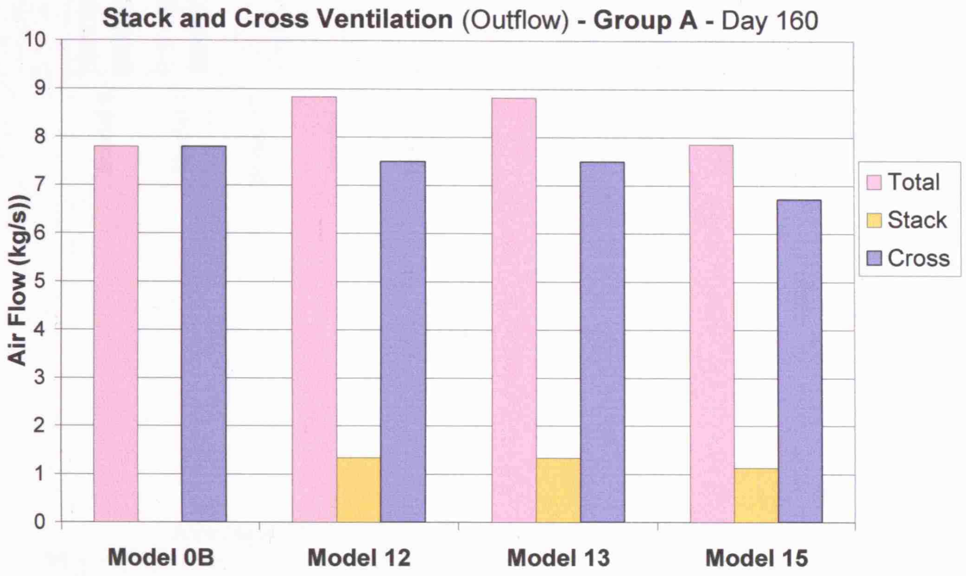
Model Modification	**Average Office Temperature** (C°)		**Average Air Flow** (Kg/s)			**Average Air Flow** (Kg/s)	
	Day	**Night**	**Total**	**Stack**	**Cross**	**Day**	**Night**
Model 0 Base Model	28.32	21.18	6.6	0	6.6	11.89	2.82
Model 0S M0 Sheltered	30.57	22.74	1.49	0	1.49	1.27	1.65
Model 0B M0 double floors	28.19	20.71	7.8	0	7.8	12.21	4.66
Model 1 Model 0 + solar chimney	28.25	20.79	7.65	1.62	6.03	13.34	3.59
Model 1C Model 1 < Width 50%	28.28	20.96	7.37	1.01	6.36	13.00	3.35
Model 2 Model 1 sheltered	29.78	22.07	2.20	1.31	0.89	2.07	2.3
Model 3 Model 1 > top aperture	28.25	20.78	7.71	1.74	5.97	13.43	3.63
Model 4 Model1 top ap orientation	28.53	20.88	7.77	0.73	7.04	13.36	3.77
Model 5A chimney height 50%	28.22	20.74	7.84	1.80	6.03	13.54	3.76
Model 5B chimney height 100%	27.80	19.61	7.97	1.96	6.00	13.78	3.82
Model 6 2 top apertures (N&S)	28.31	20.79	9.45	3.16	6.47	16.77	4.21
Model 6S Model 6 sheltered	29.77	21.78	2.37	1.55	0.82	2.19	2.51
Model 7 increase insulation	28.24	20.76	7.64	1.63	6.01	13.33	3.58
Model 8 sloped chimney top	28.25	20.78	7.65	1.62	6.03	13.34	3.61
Model 9 > absorptance	28.26	20.83	7.69	1.66	6.03	13.37	3.64
Model 10 center location	28.12	20.71	7.35	1.40	5.95	13.03	3.28
Model 10B Model 10 > top aperture	28.12	20.75	7.33	1.49	5.84	12.98	3.29
Model 12 double floor	28.15	20.55	8.83	1.34	7.49	13.50	5.49
Model 13 Model12 > therm mass	28.15	20.55	8.82	1.33	7.49	13.50	5.47
Model 15 Model 10 + Model 13	28.03	20.47	7.85	1.13	6.72	13.00	4.18

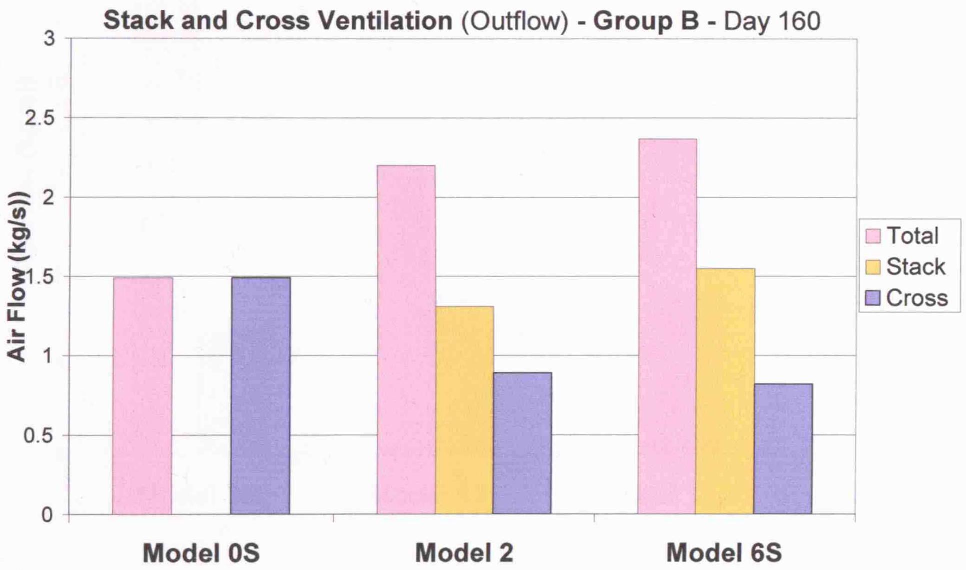
APPENDIX 4

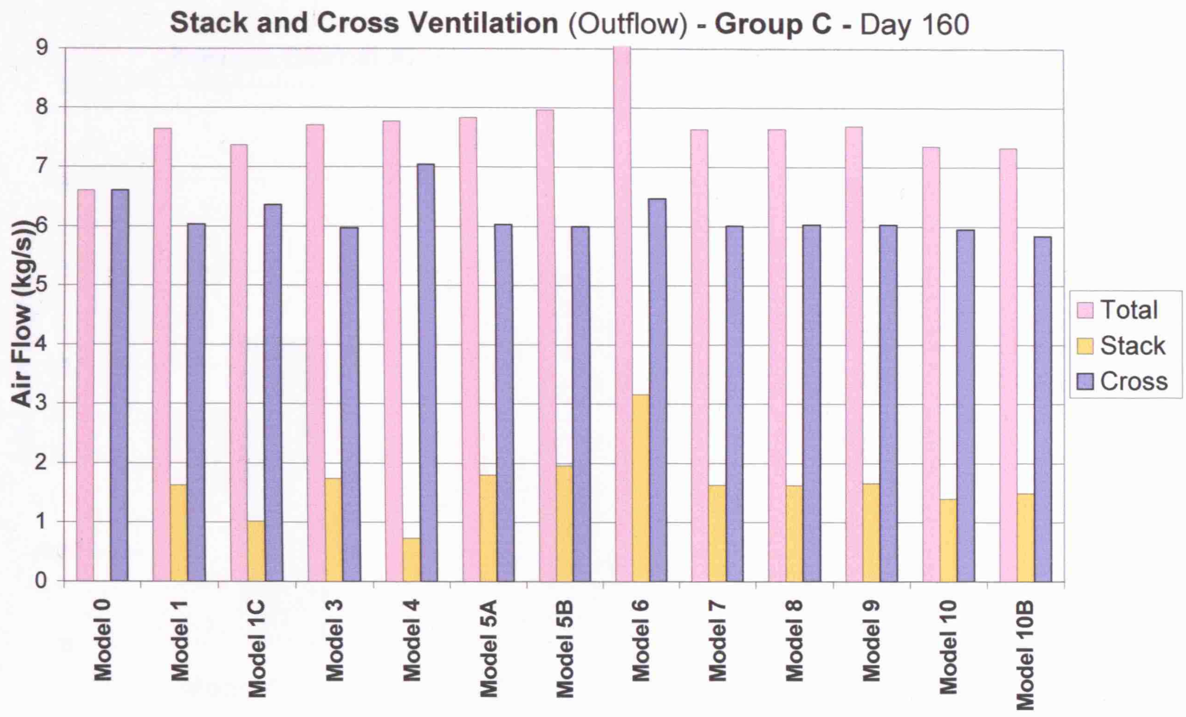
Group Air Flow Comparison – Simulation DAY 160

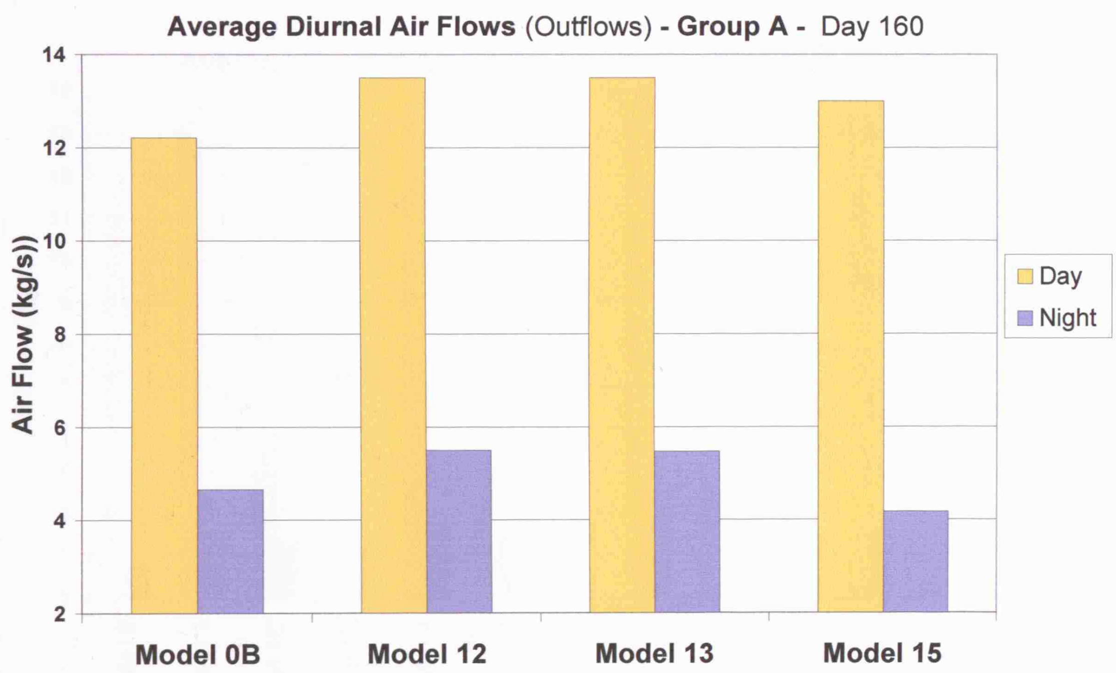
Due to the considerable variation in amplitude of the different types of ventilation results are further examined in 3 groups:

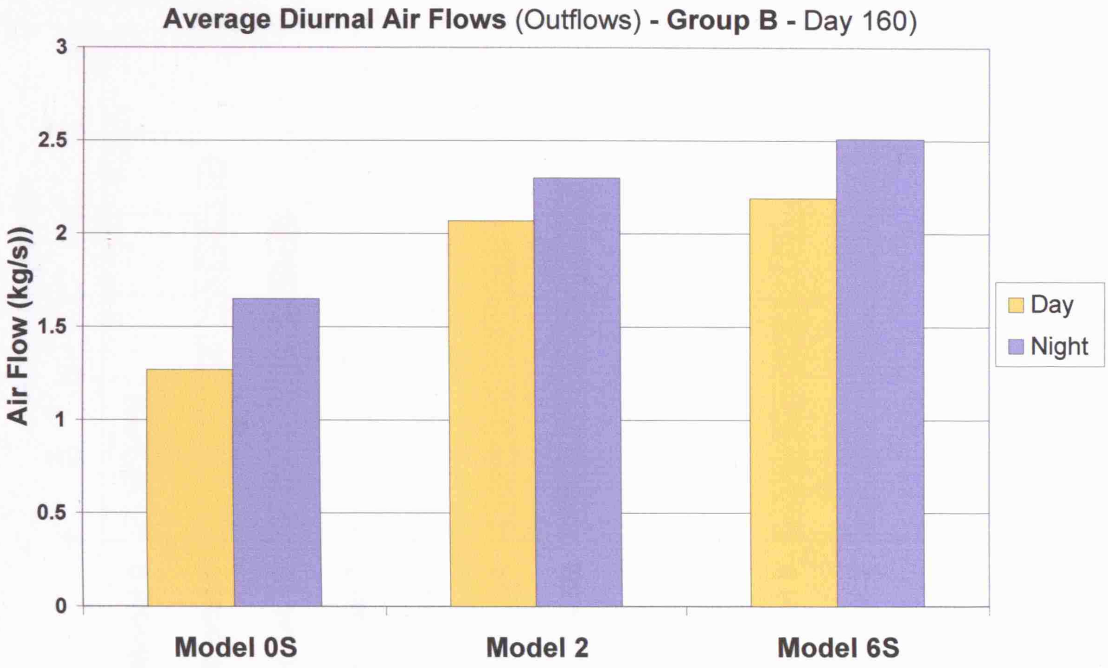
- Group A: Models with double floors/ enhanced thermal mass and increased apertures: Model 0B, Model 12, Model 13 and Model 15
- Group B: Models simulated under no wind conditions: Model 0S, Model 2 and Model 6S)
- Group C: All other models.

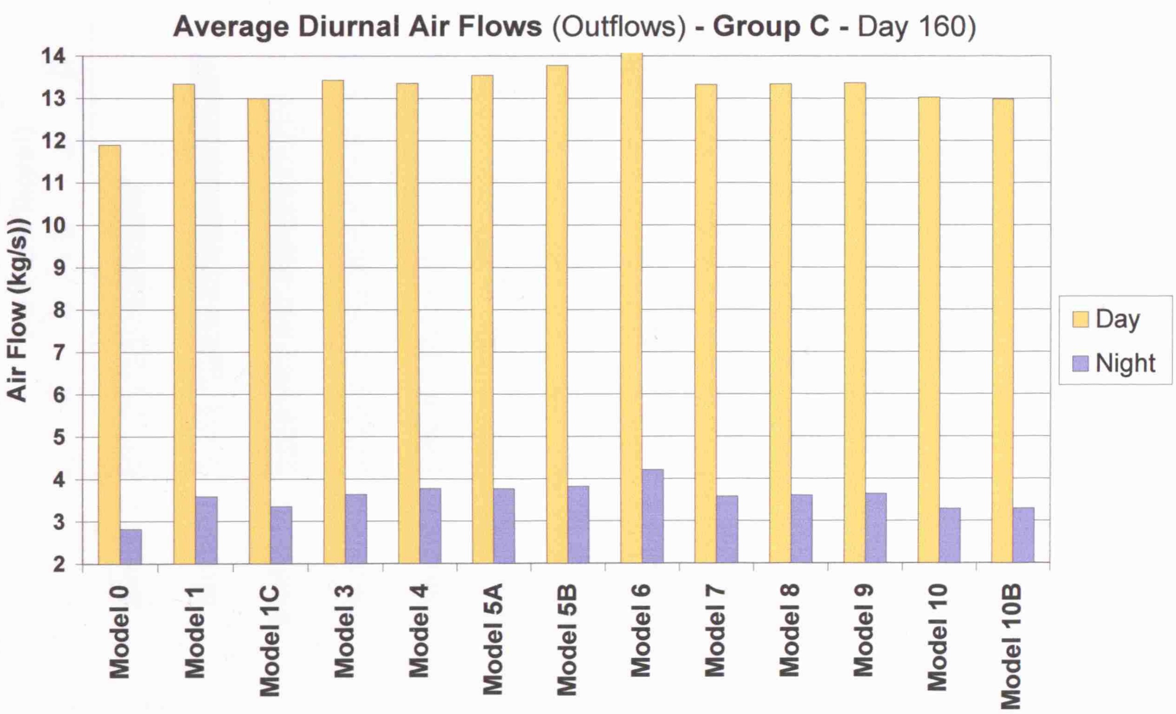


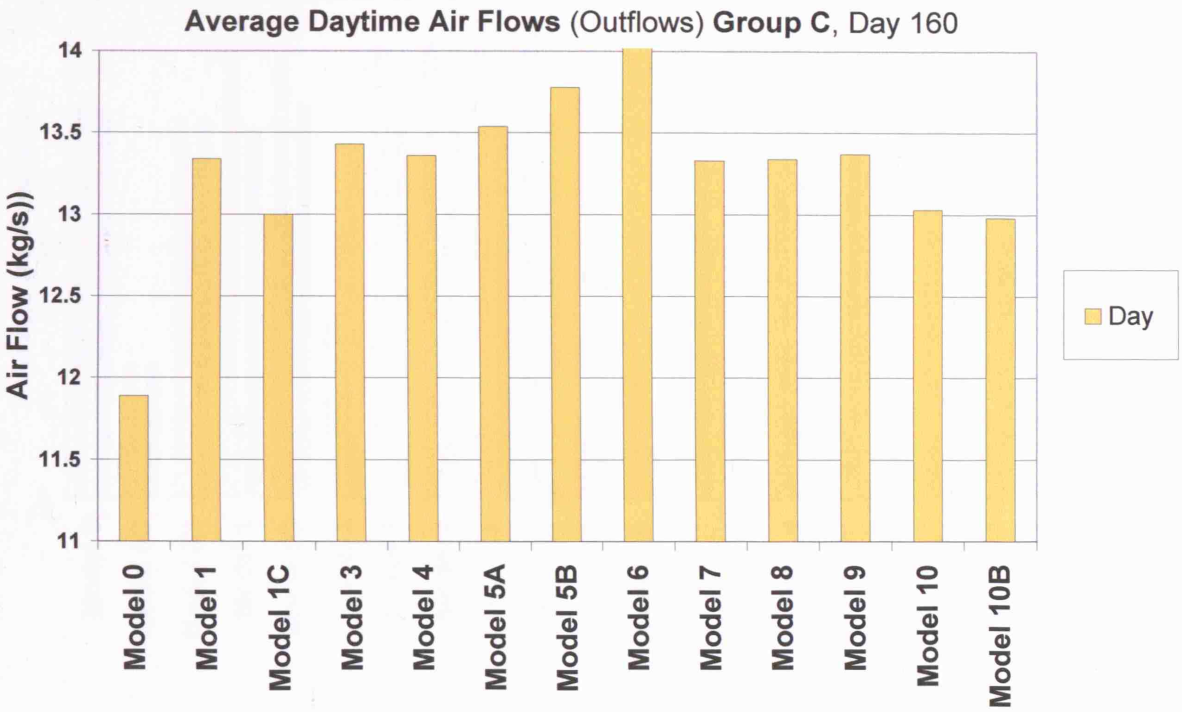


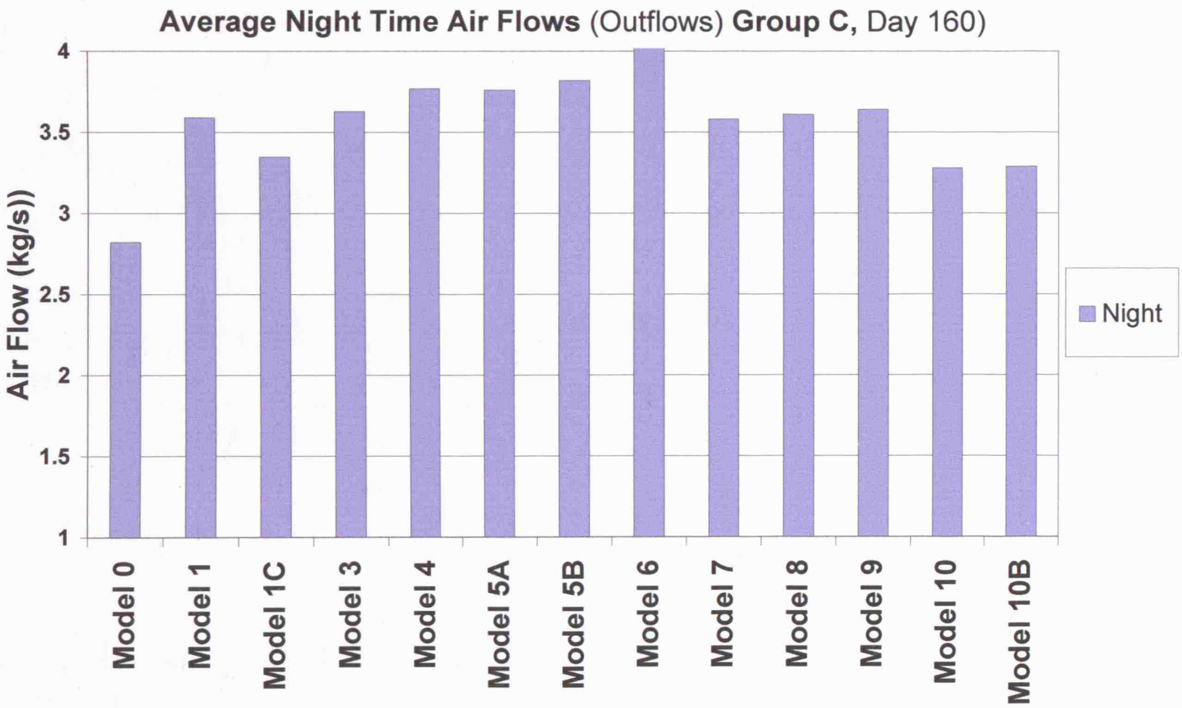

Stack and Cross Ventilation (Outflow) - Group C - Day 160
Air Flow (kg/s))
0
1
2
3
4
5
6
7
8
9
Total
Stack
Cross
Model 0
Model 1
Model 1C
Model 3
Model 4
Model 5A
Model 5B
Model 6
Model 7
Model 8
Model 9
Model 10
Model 10B

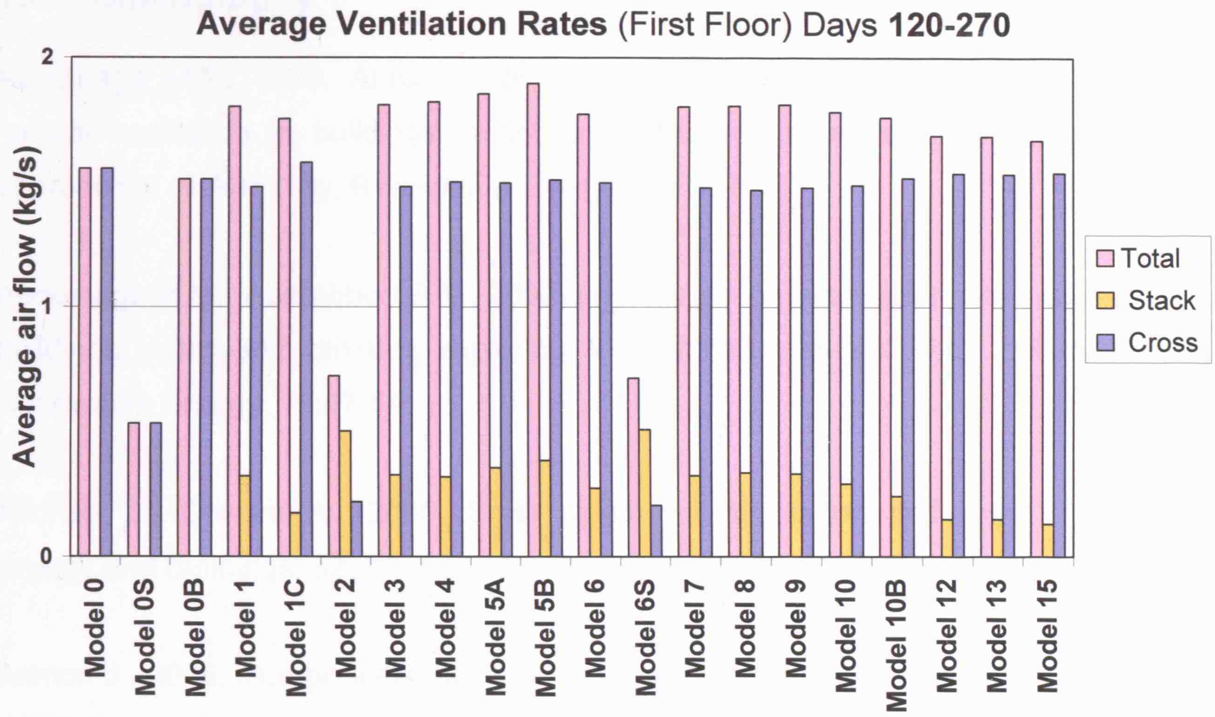

Average Diurnal Air Flows (Outflows) - Group A - Day 160
Air Flow (kg/s))
2
4
6
8
10
12
14
Day
Night
Model 0B
Model 12
Model 13
Model 15


Average Diurnal Air Flows (Outflows) - Group B - Day 160)
Air Flow (kg/s))
3
2.5
2
1.5
1
0.5
0
Model 0S
Model 2
Model 6S
Day
Night


Average Diurnal Air Flows (Outflows) - Group C - Day 160)
Air Flow (kg/s))
14
13
12
11
10
9
8
7
6
5
4
3
2
Model 0
Model 1
Model 1C
Model 3
Model 4
Model 5A
Model 5B
Model 6
Model 7
Model 8
Model 9
Model 10
Model 10B
Day
Night


Average Daytime Air Flows (Outflows) Group C, Day 160
Air Flow (kg/s))
14
13.5
13
12.5
12
11.5
11
Model 0
Model 1
Model 1C
Model 3
Model 4
Model 5A
Model 5B
Model 6
Model 7
Model 8
Model 9
Model 10
Model 10B
Day


Average Night Time Air Flows (Outflows) Group C, Day 160)
Air Flow (kg/s))
4
3.5
3
2.5
2
1.5
1
Model 0
Model 1
Model 1C
Model 3
Model 4
Model 5A
Model 5B
Model 6
Model 7
Model 8
Model 9
Model 10
Model 10B
Night


Average Ventilation Rates (First Floor) Days 120-270
Average air flow (kg/s)
2
1
0
Total
Stack
Cross
Model 0
Model 0S
Model 0B
Model 1
Model 1C
Model 2
Model 3
Model 4
Model 5A
Model 5B
Model 6
Model 6S
Model 7
Model 8
Model 9
Model 10
Model 10B
Model 12
Model 13
Model 15

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